(Recent ≥Jan 2024 results on)

SM Higgs properties and rare decays in ATLAS

Marc Escalier, IJCLab Orsay/France, on behalf of ATLAS Collaboration

(see other presentation by Ruggero Turra, ATLAS searches in the Higgs sector for $H_{\neq 125}$)

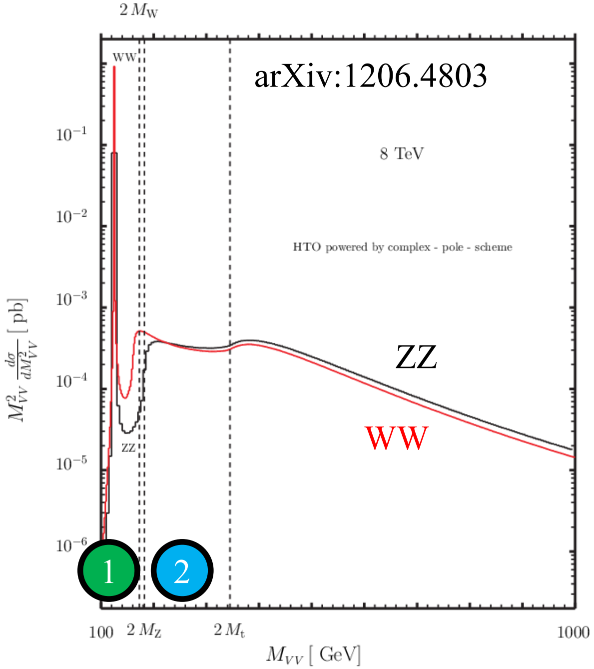
With the full Run 2 pp collision dataset collected at 13 TeV, very precise measurements of Higgs boson properties and its interactions can be performed, shedding light over the electroweak symmetry breaking mechanism. This talk presents measurements performed using the Run 2 dataset, as well as first results using the Run 3 pp collision dataset collected since 2022 at 13.6 TeV. Measurements of the Higgs boson properties by the ATLAS experiment in various decay channels are shown, including its production cross sections, simplified template cross sections, mass, width, CP quantum number, differential and fiducial cross sections, as well as their combination and interpretations. Specific scenarios of physics beyond the Standard Model are tested, as well as a generic extension in the framework of the Standard Model Effective Field Theory. The talk also presents the latest HH searches, which are sensitive to the Higgs boson self-coupling. results are shown in terms of sensitivity to the SM HH production and limits on the Higgs boson self-coupling.

Overview analyses presented

			Production modes					
			Inclusive/combined	ggH	VBF	WH	ZH	ttH
H		Combination	ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=139 fb^{-1}, JHEP 11 (2024) 097 February 2024					
		$H\rightarrow\gamma\gamma + H\rightarrow ZZ^*\rightarrow 4l$	Run 3, $\sqrt{s}$=13.6 TeV, L=29.0-31.4 fb^{-1}, EPJC 84 (2024) 78, June 2023					
	bosons	$H\rightarrow ZZ^*\rightarrow 4l$	ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-298 , off-shell, NSBI, Γ_H, December 2024					
	fermions	$H\rightarrow bb$				Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-237, October 2024 (WH and ZH, H→bb and H→cc)		ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-194, July 2024
		$H\rightarrow cc$						
		$H\rightarrow\tau\tau$	Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-198, July 2024					
	rare	$H\rightarrow\gamma\gamma$ +c	ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-175, July 2024					
		$H\rightarrow D^*\gamma$ flavour violation coupling	ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=136.3 fb^{-1}, PLB 855 (2024) 138762, February 2024					
HH		combination	ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126-140 fb^{-1}, PRL 133 (2024) 101801, June 2024					
HHH			ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126 fb^{-1}, CERN-EP-2024-285, Nov. 2024					

Γ_H with $H^* \to ZZ \to 4l$

ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, CERN-EP-2024-298, Dec. 2024



$$\frac{d\sigma^{H\to VV}}{dm_{VV}^2} \propto \frac{g_{prod}^2(\hat{s})\, g_{decay}^2(\hat{s})}{m_H^2\Gamma_H^2 + (m_{VV}^2 - m_H^2)^2}$$

(1) $\sigma_{on-shell}^{H\to VV} \propto \frac{g_{prod}^2(m_H)\, g_{decay}^2(m_H)}{\Gamma_H}$

H on-shell

1 Z off shell

(2) $\frac{d\sigma_{off-shell}^{H^*\to VV}}{dm_{VV}^2} \propto g_{prod}^2(\hat{s})\, g_{decay}^2(\hat{s})$

H off-shell: 10% contribution

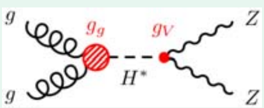
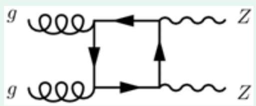
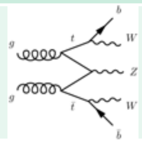
Z on shell

→disentangle Γ_H

(if no BSM altering on, off- couplings differently for ggH (loop), HZZ)

- Considers various processes: S, B, interference, non-interference terms

(here example is for gg, but considers also EW (qq))

S	B	I	NI (non-interfering)
$\lvert\mathcal{M}_S\rvert^2 \propto g_g^2 g_V^2$	-	$2\mathcal{Re}(\mathcal{M}_S\mathcal{M}_B^*) \propto g_g g_V$<0	
			

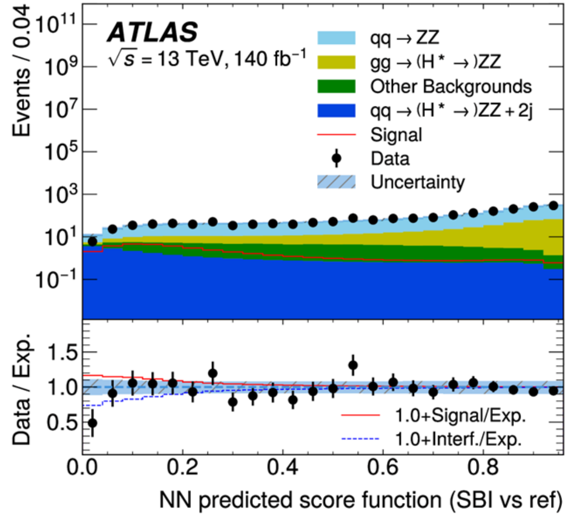
Unique scaling for each component→pdf=f(κ_g, κ_V)

Γ_H with $H^* \rightarrow ZZ \rightarrow 4l$

- Selection

Kinematics, Higgs off-shell: $180 < m_{4l} < 2000$ GeV
Event description using 14 obs. +preselection Neural Network (NN)
+Control Region for background

(here X=S(gg)+B+I)



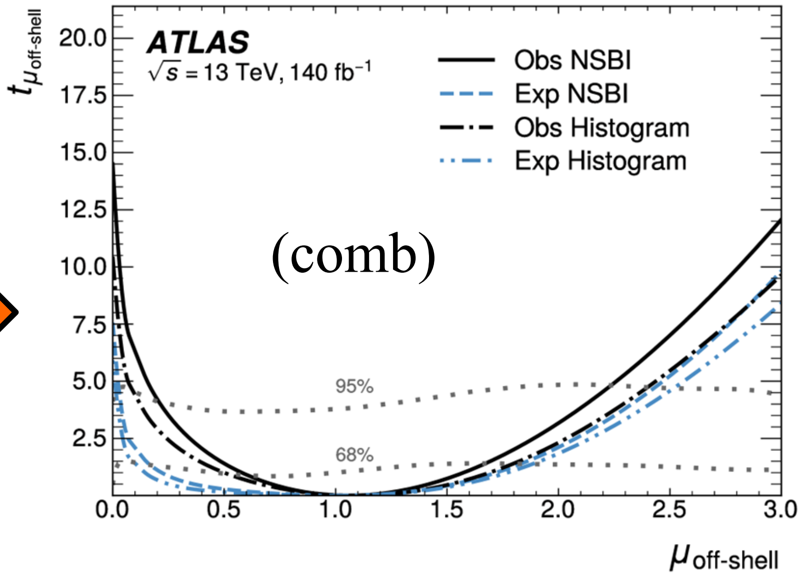
- Neural Simulation-Based Inference (NSBI)

Per-event likelihood ratio from NN from 14 observables
optimally sensitive to any value of signal strength (μ)

- Results

Z_{obs}=2.5 (Z_{exp}=1.3), $\mu_{off\text{-}shell}=0.87^{+0.75}_{-0.54}$ (exp: $1.00^{+1.04}_{-0.95}$)
Comb. w/ 2l 2ν channel: Z_{obs}=3.7 (Z_{exp}=2.4)
$\mu_{off\text{-}shell}=1.06^{+0.62}_{-0.45}$ (exp: $1.00^{+0.83}_{-0.83}$)

→evidence off-shell (already in past, PLB 846 (2023) 138223)



Combination w/ on-shell H→ZZ→4l
$\Gamma_H=4.3^{+2.7}_{-1.9}$ MeV (exp: $\Gamma_H=4.1^{+3.5}_{-3.4}$ MeV)

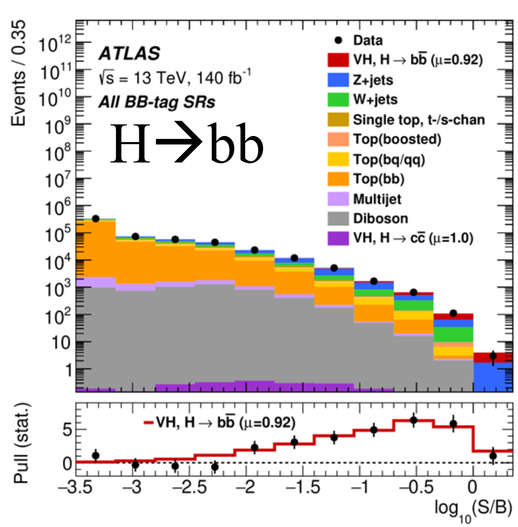
VH, H→bb, H→cc

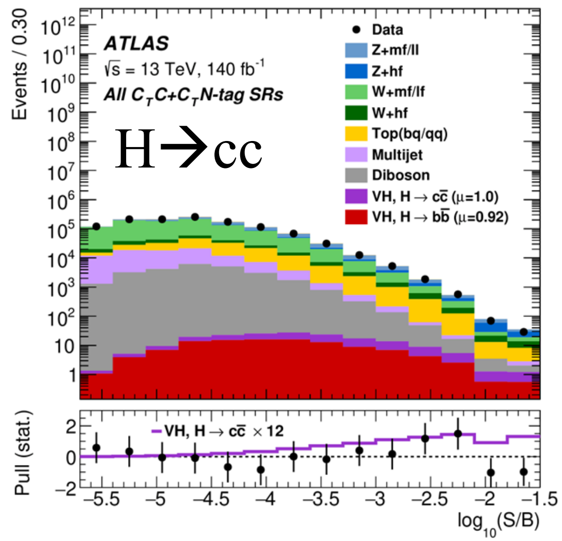
Run 2, √s=13 TeV, L=140 fb^{-1}, CERN-EP-2024-237, October 2024

- Complex selection

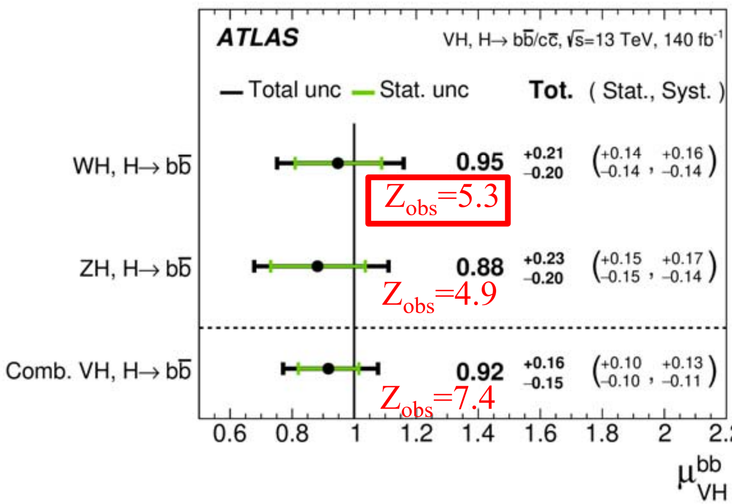
b-jet corr. : σ_{mH} improved up to 40 %
Flavour tagging & efficiency
DL1R: b: 70%, c: 45%
Categories:
V(νν/lν/ll), #b, #c, #light jets
p_T^V (resolved, boosted)
control Regions
Validation analysis: VZ (Z_{obs}>5)
Final Discriminant Variable (DV): BDTs

- Results



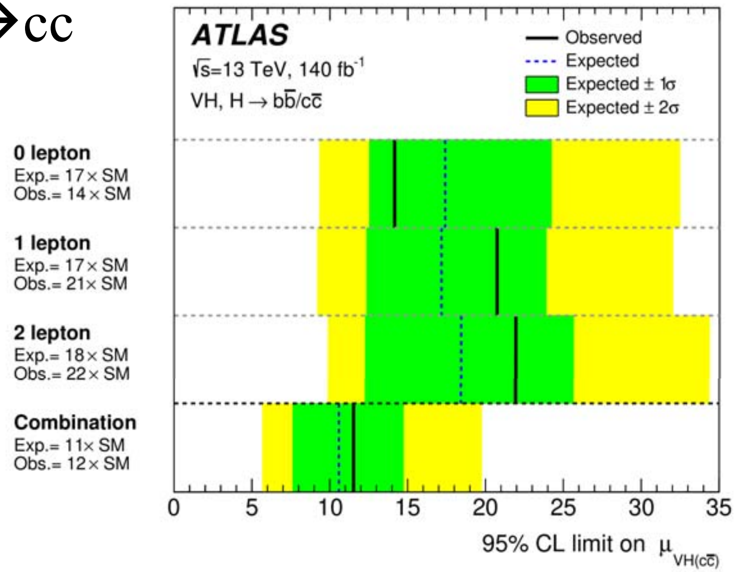


H→bb



First observation of WH, H→bb

H→cc



VH(cc) 95% CL limit: 11.5xSM

VH, H→bb, H→cc

- VH interpreted in κ-framework

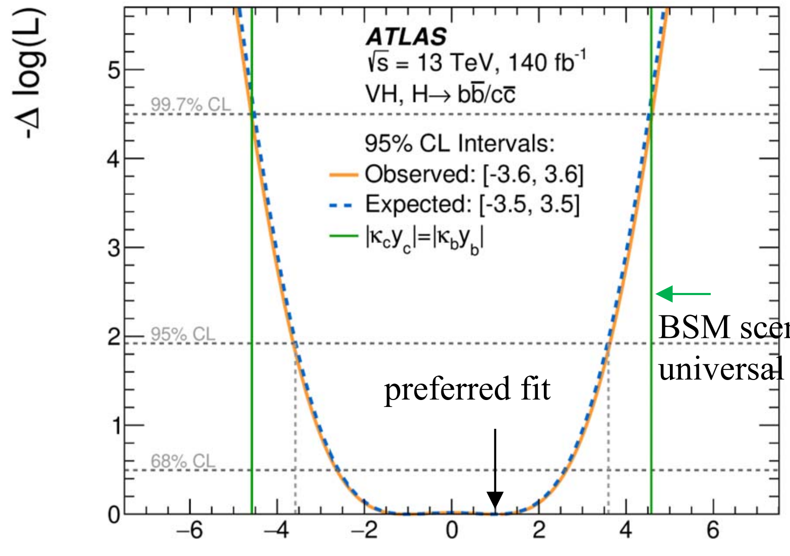
Parameterise signal strengh in amplitude scaling

$|\kappa_c/\kappa_b|$: no assumption on Γ_H

95% CL limit

obs: 3.6xSM

exp: 3.5xSM



Confirming non-universality of Hqq coupling: $Y_{hcc} < Y_{Hbb}$

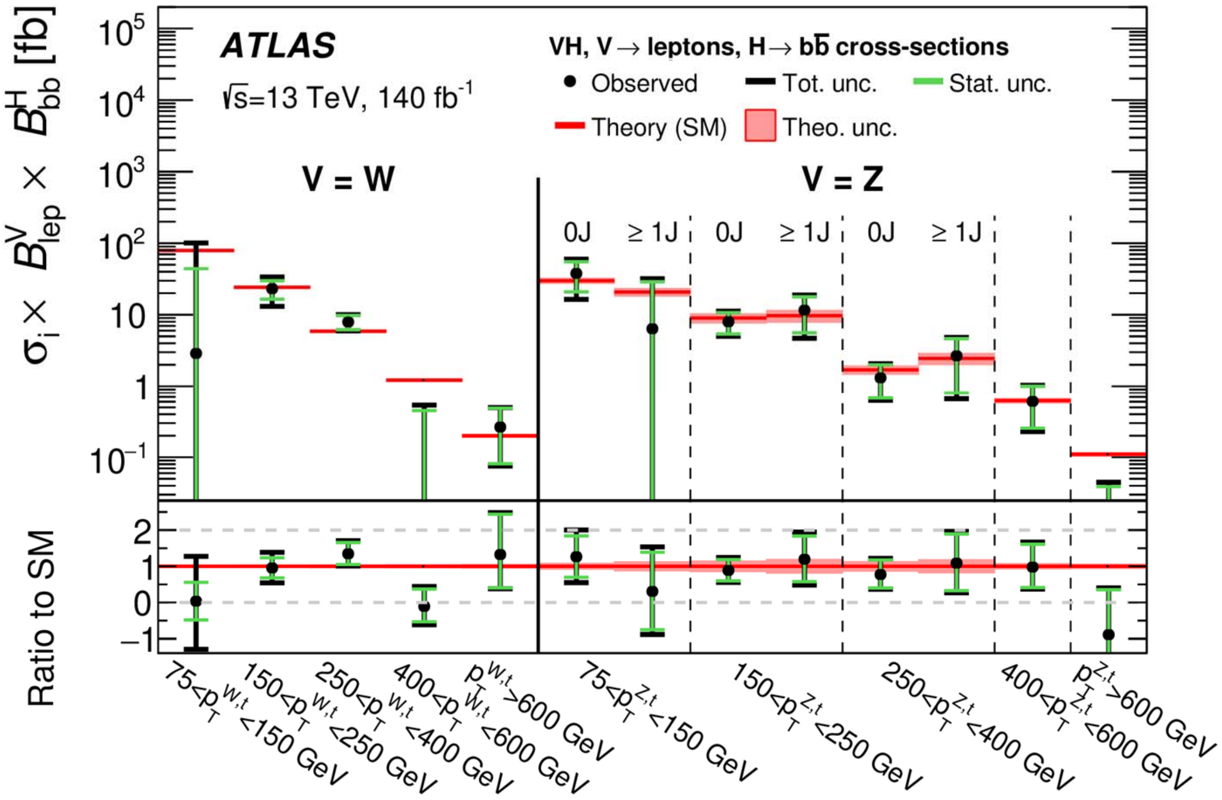
*explanation: κ_c/κ_b=(Ycc/Ybb) x (Ybb^{SM}/Ycc^{SM})

if nature would have universal couplings, there would be Ycc=Ybb

κ_c/κ_b=(Ybb^{SM}/Ycc^{SM})=4.5 for renormalisation m_H=125 GeV

- STXS (H→bb), (cross-sections in fine granularity kinematic fiducial regions)

Category mirroring fiducial regions



Compatible w/ SM

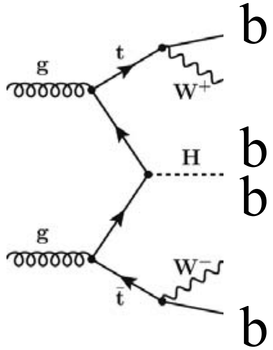
Dominated by stat uncertainty

ttH, H→bb

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-194

July 2024

- Complex final state: leptons (e, μ), jets, b-jets

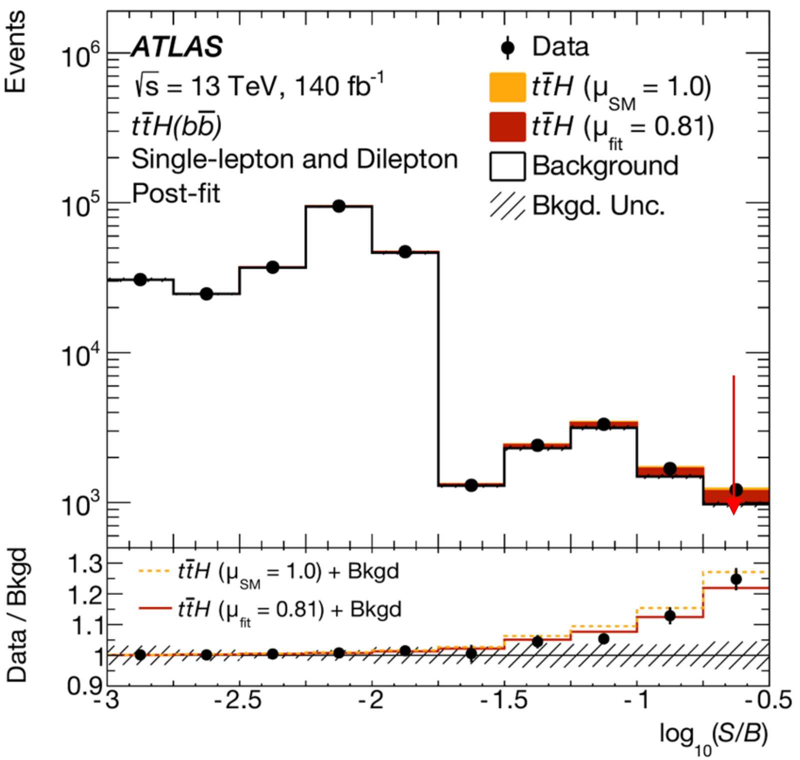


Categories: #lepton, resolved/boosted (1-lepton), #jets, #b-jets

- multiclass NN: defines SR, CR

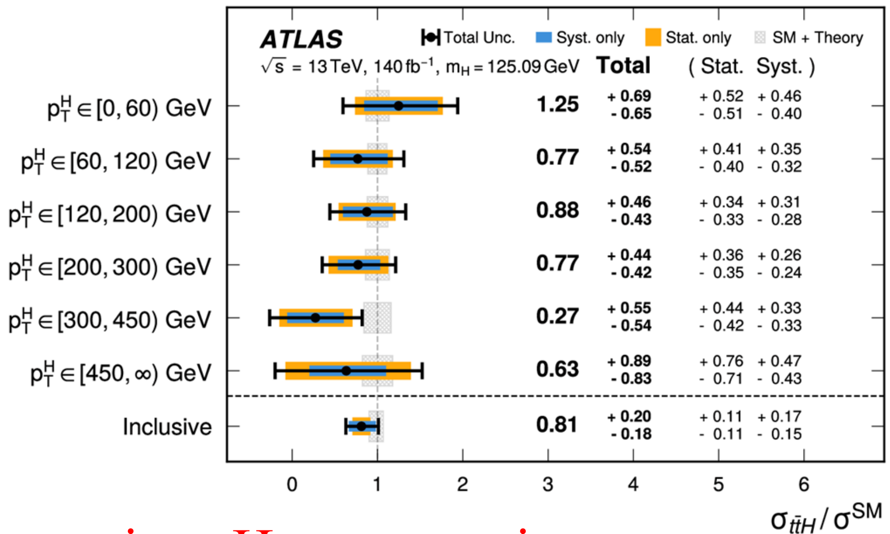
Pairing jets-Higgs: second NN to reconstruct p_T^H for STXS

- Results inclusive & STXS (bins of p_T^H)



Z_{obs}=4.6 (Z_{exp}=5.4)

$$\mu_{ttH} = 0.81 \pm 0.11\,(stat)^{+0.20}_{-0.16}\,(syst)$$



Most precise ttH cross-section measurement in a single decay channel, inclusively and in each p_T^H bin

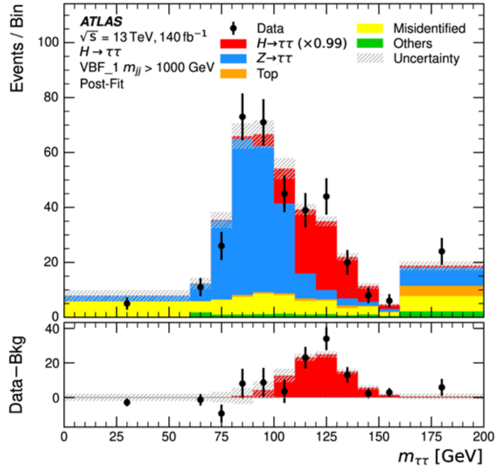
ttH, H→γγ: $\mu_{ttH} = 1.43\,^{+0.33}_{-0.31}\,(stat)\,^{+0.21}_{-0.15}\,(syst)$

PRL 125, 061802 (2020)

H→ττ, diff. measurement

Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-198, July 2024

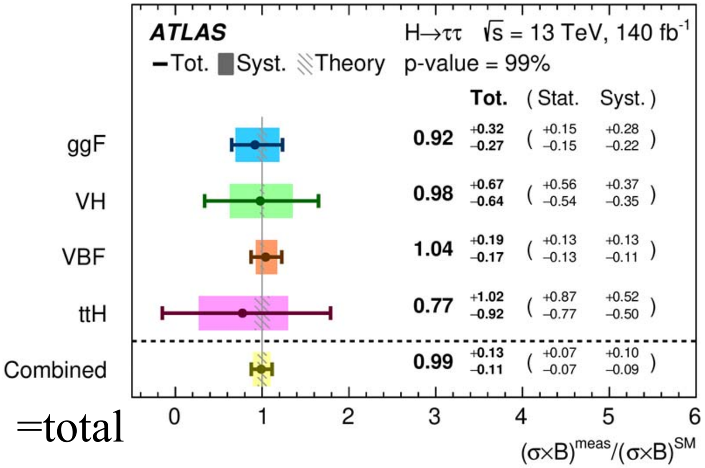
$\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_e\tau_\mu$ (different flavour)
Missing Mass Calculator: likelihood for $m_{\tau\tau}$ estimation



- Categorisation for STXS (and VBF for dσ/dX)

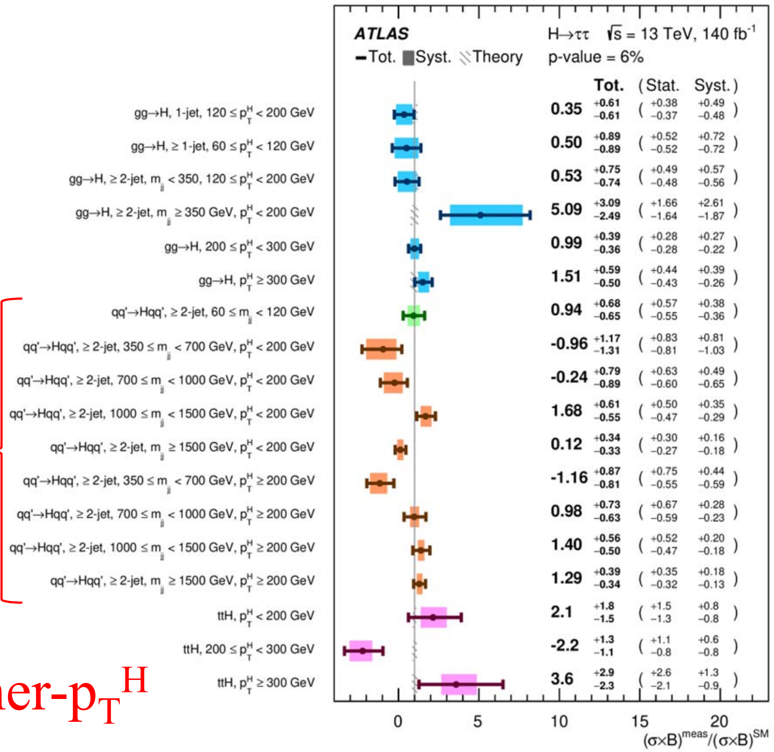
VBF, tt(0l)H, V(had)H, ggF boost (p_T^H>100 GeV), subsplit: kinematics & BDT

- Production modes



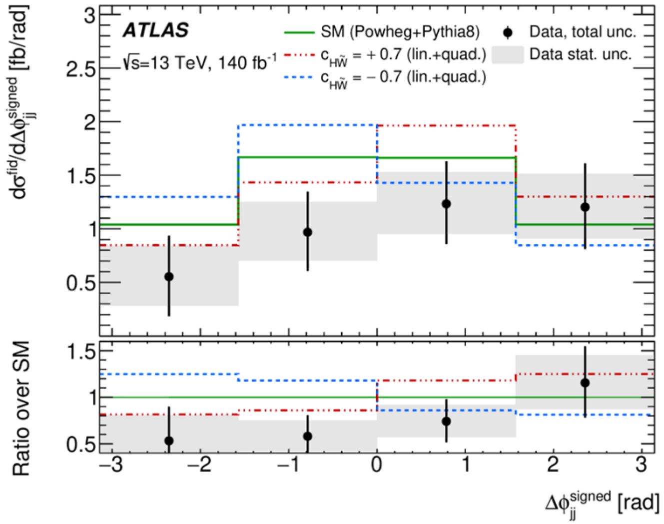
=total

- STXS



- dσ/dX w/ VBF selection

p_T^H, $\Delta\phi_{jj}^{signed}$, etc.



Interpreted in SMEFT.

Strongest constraint on CP-odd $c_{H\tilde{W}}$ for Λ=1 TeV

First VBF measurement in higher-p_T^H and most precise for lower p_T^H

Higgs combination (STXS, dσ/dX) EFT interpretation

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=139 fb^{-1}, JHEP 11 (2024) 097

- Inputs: σ prod. modes (STXS-0), STXS-1.2: $H\to\gamma\gamma$, $H\to ZZ^*\to 4l$, $H\to WW^*\to e\nu\mu\nu$, $H\to Z\gamma$, $H\to bb$, $H\to\tau\tau$, $H\to\mu\mu$, $d\sigma/dp_T^H$: $H\to\gamma\gamma$, $H\to ZZ^*\to 4l$
- Parameterisation rates: SMEFT, Warsaw basis

- Cross-section x BR: parametrized, Linear in c_i ($\sim\Lambda^{-2}$) or lin+quadratic in c_i ($\sim\Lambda^{-4}$)

Comparison: qualitative info on validity neglecting dim-8

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)}$$

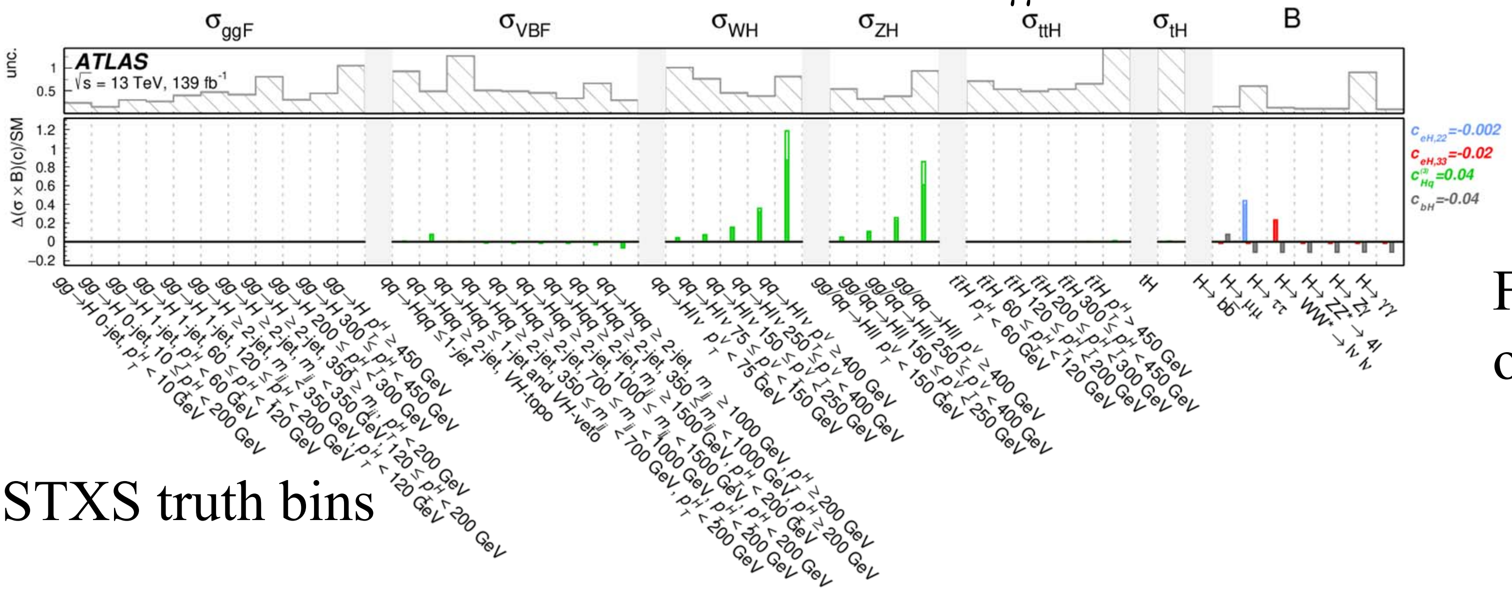
- Eff x accept: restricted kinematic region: not parametrized: theoretical systematic
- Decay: f(EFT) (no restriction to kinematic region)

2 bodies: small effect: small. >2 bodies decays : parametrisation

- Shape final discriminant: negligible effect on (eg $m_{\gamma\gamma}$ for $H\to\gamma\gamma$), else parameterised

rel $\Delta\sigma_{STXS}$

rel imp. c_i



Values chosen from sensitivity from expected uncertainty

Filled: linear

open: + quadratic

STXS truth bins

Too many operators, correlations: probe instead eigenvector

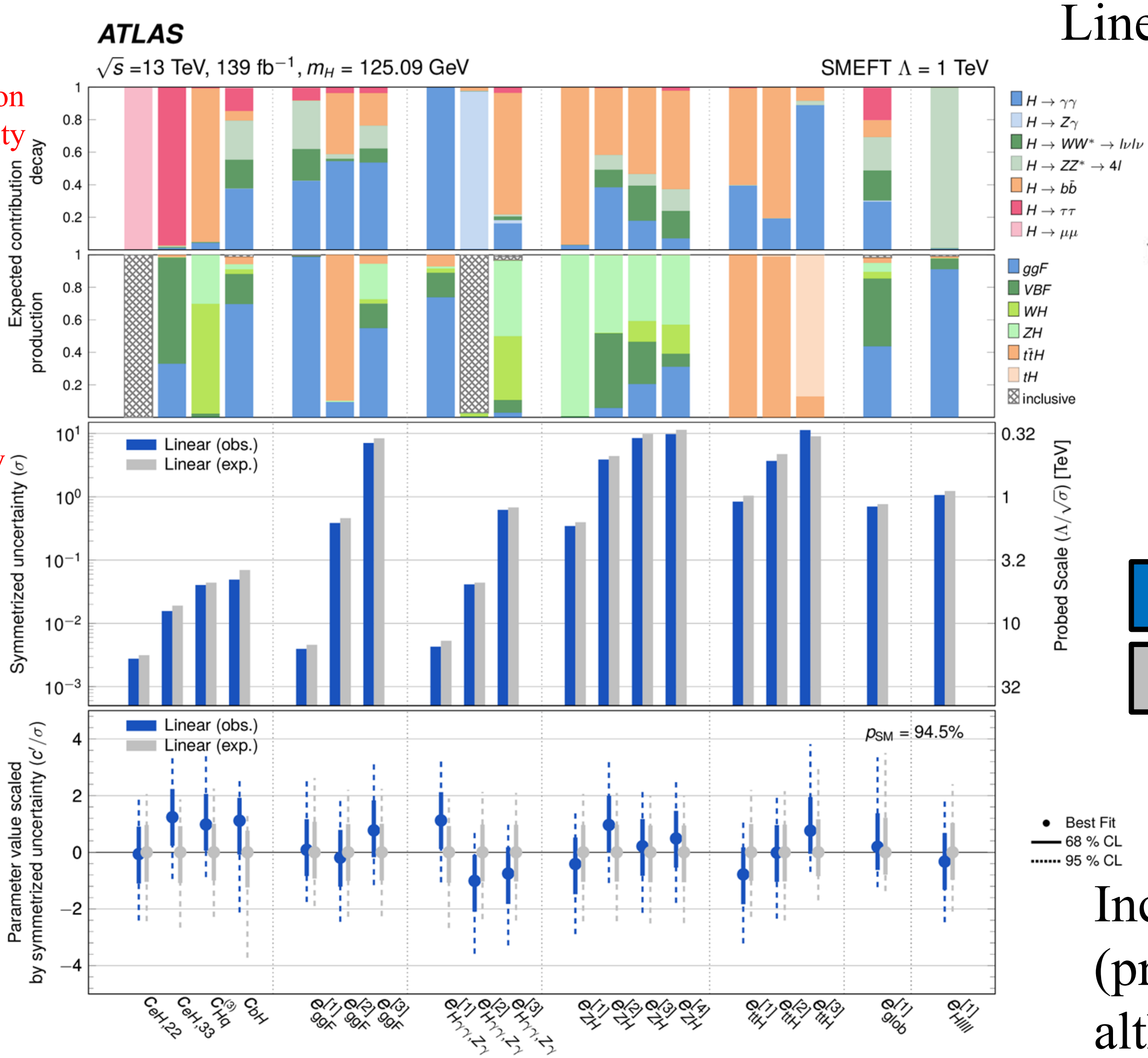
Higgs combination (STXS, dσ/dX) EFT interpretation

- Results for STXS (here linear)

Contribution to sensitivity of c_i

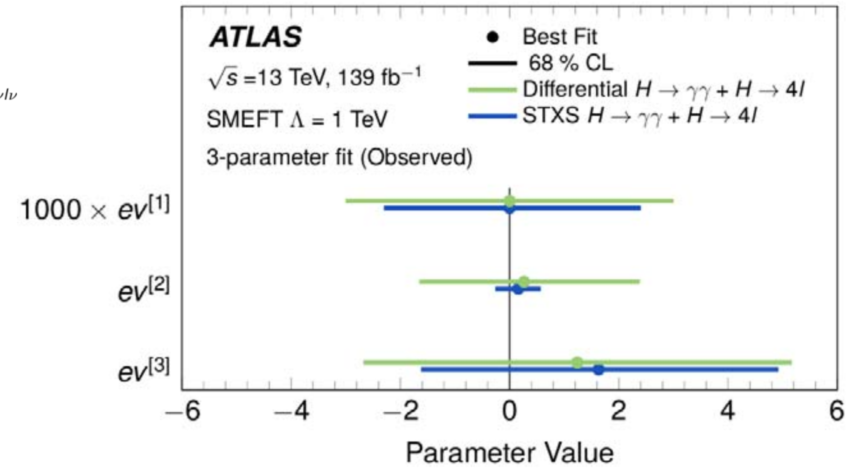
uncertainty

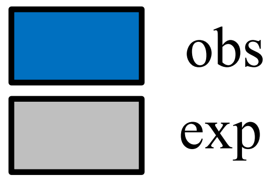
pull



- Results for $d\sigma/dp_T^H$, $H \rightarrow \gamma\gamma$, $H \rightarrow 4l$

Linear only; eigenvectors different





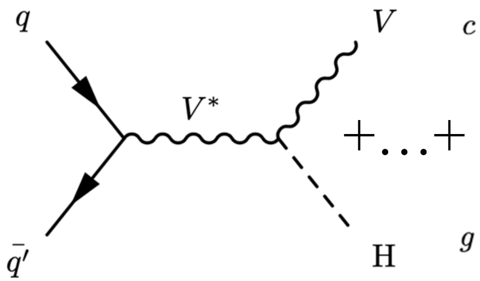
Increased sensitivity from STXS (production modes, many variables, although lower granularity than p_T^H)

- Also interpreted in 2HDM & MSSM: 8 benchmarks (see backup)

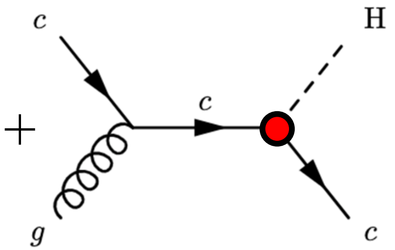
Very rare decays

- $H\rightarrow\gamma\gamma + c$

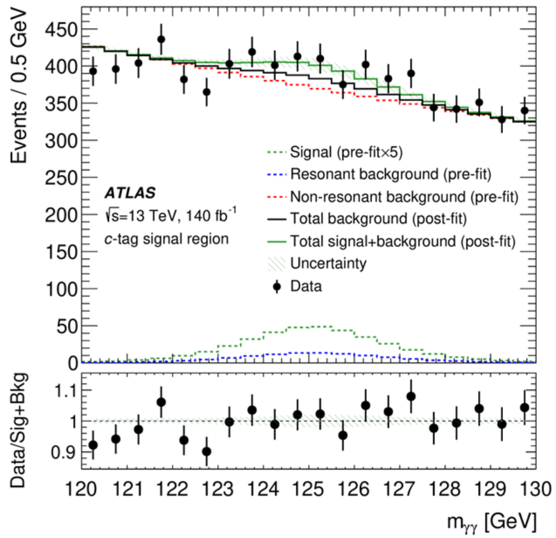
ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-175, July 2024



+…+



Yukawa Hcc
(1% only of whole process)



- 95% CL upper limit

obs: 10.4 pb

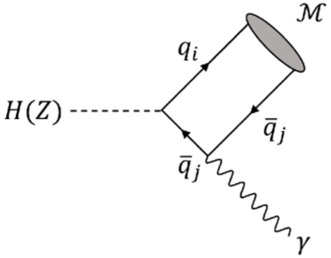
exp: 8.6 pb

First search of this production

- $H\rightarrow D^*(D^0\pi^0, D^0\gamma)\gamma$,

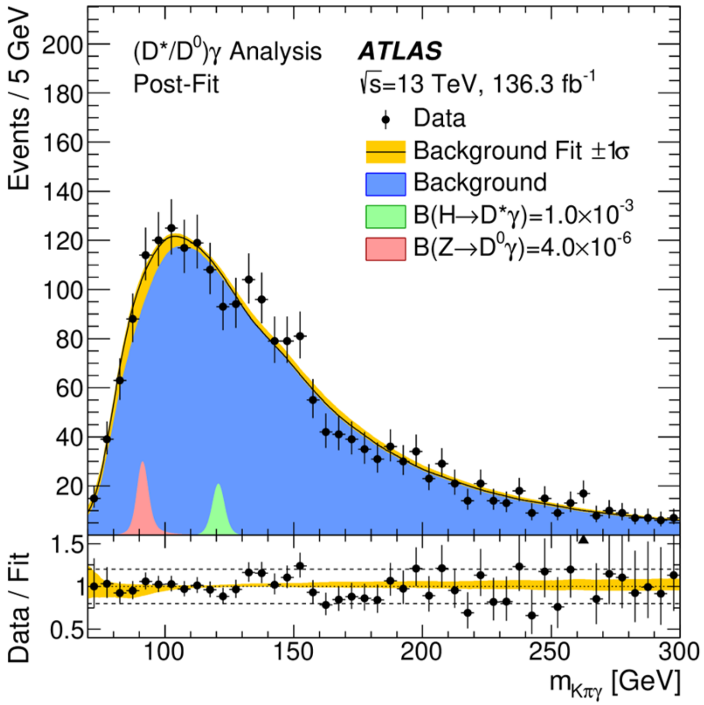
ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=136.3 fb^{-1}, PLB 855 (2024) 138762, February 2024

$D^0\rightarrow K^-\pi^+$, D^0: $c\bar{u}$ (& conjugate)



Rare, loop contributions (BR=7x10^{-27})

Probe flavour-violating coupling: BSM



95% UL on BR

obs: 1.0x10^{-3}

exp: $1.2^{+0.5}_{-0.3}$ x 10^{-3}

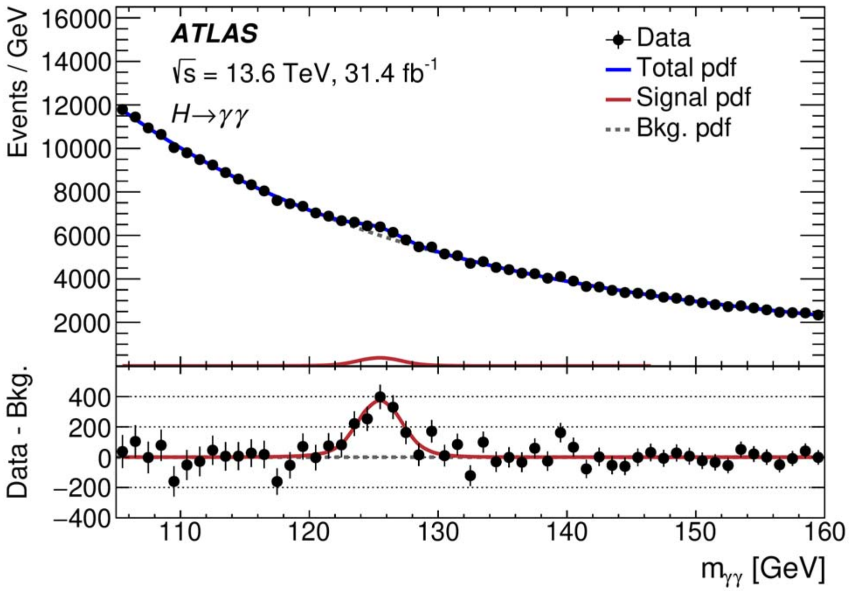
First limit

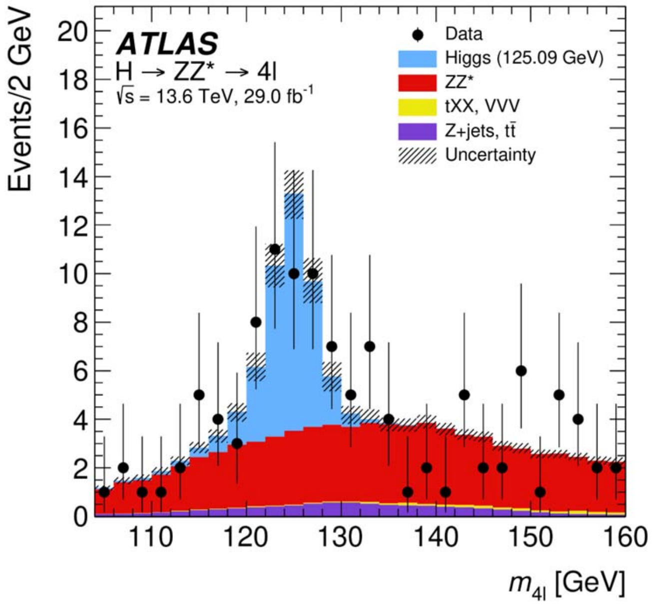
Run 3 H→γγ + H→ZZ* cross-section measurement

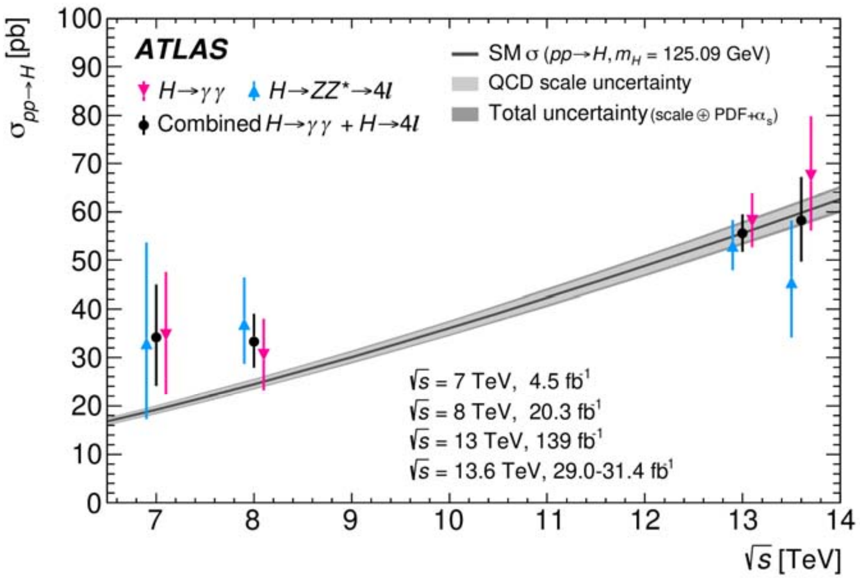
Run 3, √s=13.6 TeV, L=29.0-31.4 fb^{-1}, EPJC 84 (2024) 78, June 2023

H→γγ+H→ZZ*→4l, measurement at m_H=125.09 ± 0.24 GeV
Fiducial cross-section, then extrapolated to full phase space

(not a 'new' result)





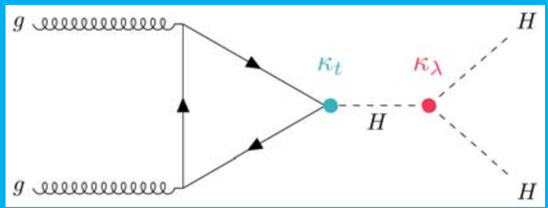


Excellent agreement w/ energy dependence
Dominated by stat. uncertainty
(note: 'today', 183 fb^{-1} available)

HH

- **Non-resonant**

ggF



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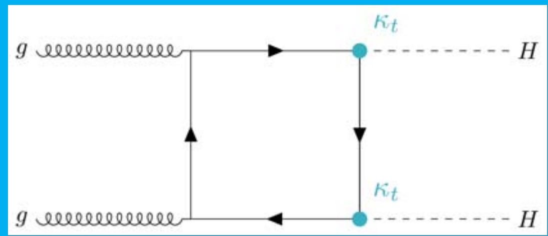
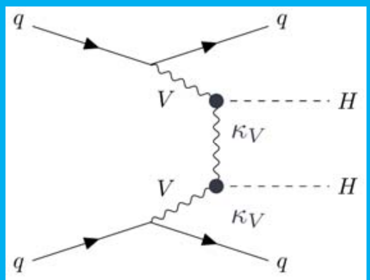
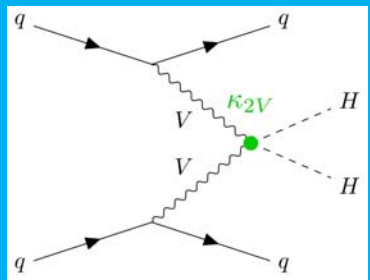
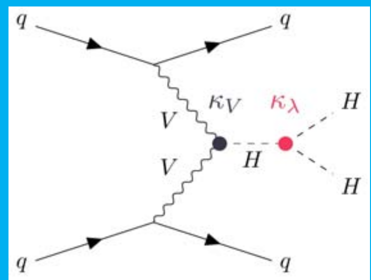


VBF







- **Resonant: see** Ruggero Turra presentation

$$\mu_{ggF\ HH} = \sigma_{ggF\ HH}/\sigma^{SM}_{ggF\ HH}$$
$$\mu_{VBF\ HH} = \sigma_{VBF\ HH}/\sigma^{SM}_{VBF\ HH}$$

$$\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$$
$$\kappa_V = g_{HVV}/g^{SM}_{HVV}$$
$$\kappa_{2V} = g_{HHVV}/g^{SM}_{HHVV}$$

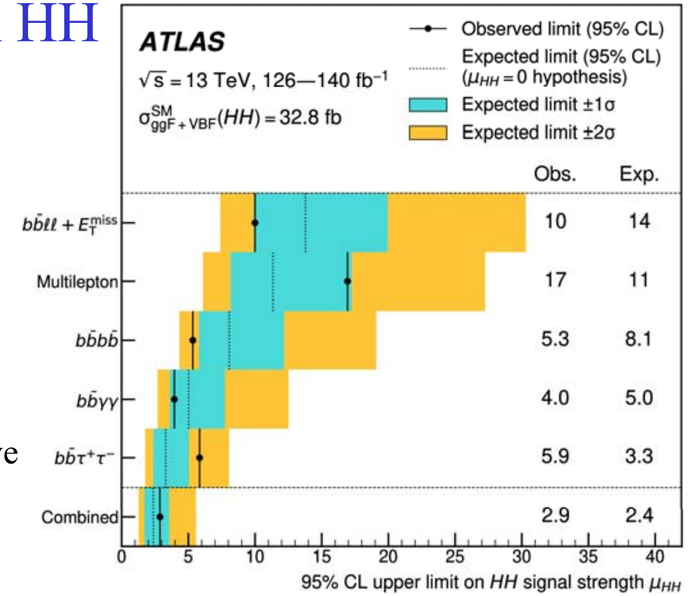
Non-resonant HH Combination

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126-140 fb^{-1}, PRL 133 (2024) 101801, June 2024

- Channels (overlap data & MC: <1% in SR⇔negligible) f(κ_λ) of 1-H neglected

bbbb (resolved, boosted), bb$\tau\tau$ (1 τ_{had}⊥ bbll+MET), bb$\gamma\gamma$, multilepton (bbZZ*, VV*VV*, VV*$\tau\tau$, $\tau\tau\tau\tau$, $\gamma\gamma$VV*, $\gamma\gamma\tau\tau$)
, bbll+MET (bb + (ZZ*, WW*, $\tau\tau$)→ll)

- Final DV: m_{HH}, $m_{\gamma\gamma}$, MVA
- Limit on HH



most sensitive

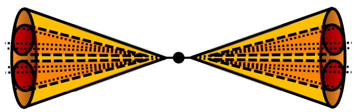
Z_{obs}=0.4
Z_{exp}=1.0

expected: 17% improvement wrt PLB 843 (2024) 137745
13%: bb$\tau\tau$, bb$\gamma\gamma$, bbbb | 4%: add multilepton, bbll+MET

κ_λ, 95 % CL
obs :]-1.2 ; 7.2[
exp:]-1.6 ; 7.2[bb$\gamma\gamma$ most sensitive

κ_{2V}, 95 % CL
obs :]0.6 ; 1.5[
exp :]0.4 ; 1.6[

bbbb most sensitive:
(boosted & deficit in data)



Best expected sensitivy to date on μ_{HH} & κ_λ

- HEFT constraints bb$\tau\tau$, bb$\gamma\gamma$, bbbb

95% CL intervals

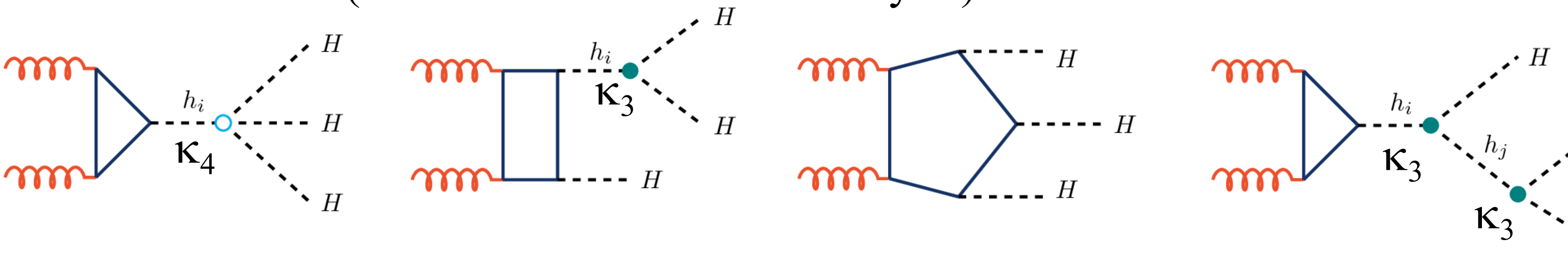
obs: $-0.38<c_{gghh}<0.49$ (exp: $-0.36<c_{gghh}<0.36$)
$-0.19<c_{tthh}<0.70$ (exp: $-0.27<c_{tthh}<0.66$)

Most stringent constraints to date

HHH bb bb bb

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126 fb^{-1}, CERN-EP-2024-285, Nov. 2024

Non Resonant (includes also a resonant analysis)



h: H

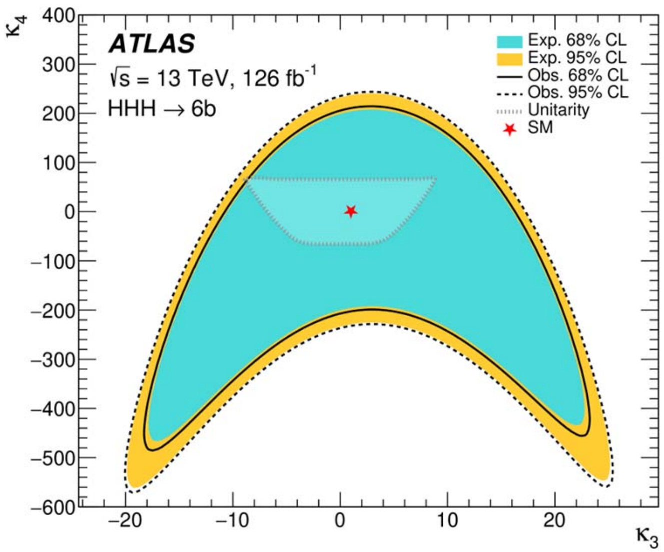
- Pairing (61% efficiency); over all pairs, minimize $|m_{H1}$-120 GeV$|+|m_{H2}$-115 GeV$|+|m_{H3}$-110 GeV$|$
  values: detector effects, energy lost from neutrinos, out-of-cone radiation

Categories: SR: 6b, CR: 4b, 5b

Bkg: dominated by QCD multijets; data-driven; extrapolate from CR
Profile likelihood, DNN

- Limit μ_{HHH}: 750xSM

  95% CL intervals
  For κ_4=1, -11<κ_3<17
  For κ_3=1, -230<κ_4<240



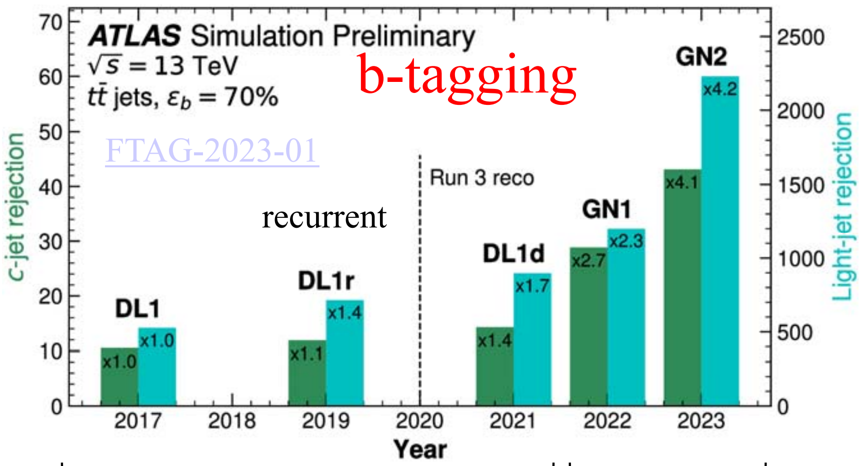
Conclusions

- Higgs Width w/ NSBI, $\Gamma_H=4.3^{+2.7}_{-1.9}$ MeV
- Update results for (VH, ttH)→bb, VH→cc, H→ττ
- EFT interpretation of Higgs combinations
- HH comb: 95% CL limit: 2.9xSM
- HHH search already started

So far, SM never been faulted in Higgs sector

- Prospects

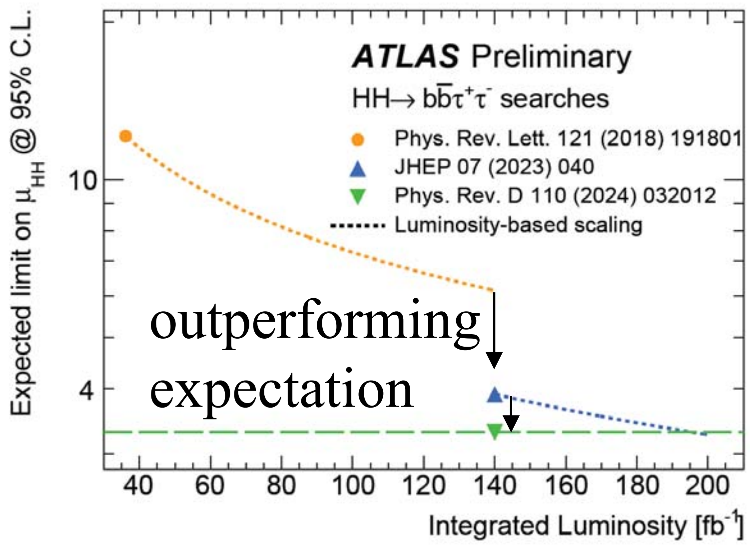
Run 3: already more stat than Run 2 (∫L, #interactions per bunch crossing, σ (higher energy)



Neural Network Graph Neural Network

bbττ: illustrative proxy

ATL-PHYS-PUB-2024-016



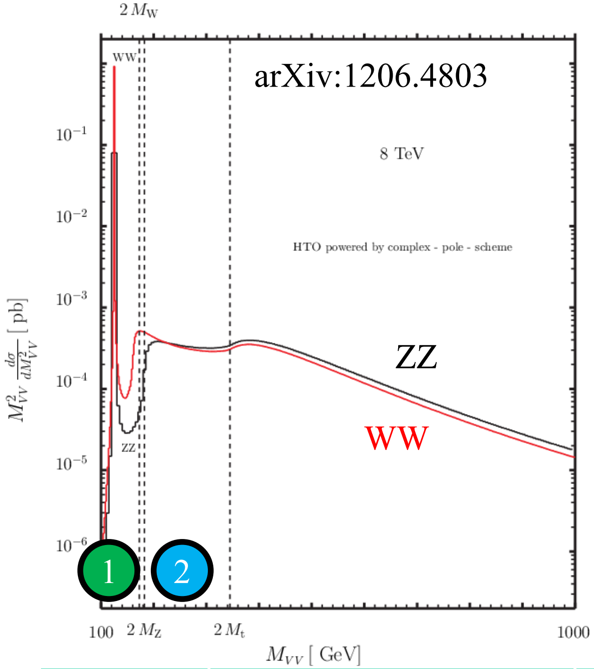
To follow future developments. Thank you for your attention

See also ATLAS HL-LHC, upgrade, physics prospects, Savanna Shaw

Backup

Γ_H with $H^* \rightarrow ZZ \rightarrow 4l$

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-298



$$\frac{d\sigma^{H\rightarrow VV}}{dm^2_{VV}} \propto \frac{g^2_{prod}(\hat{s})\,g^2_{decay}(\hat{s})}{m^2_H\Gamma^2_H + (m^2_{VV} - m^2_H)^2}$$

(1) $\sigma^{H\rightarrow VV}_{on-shell} \propto \frac{g^2_{prod}(m_H)\,g^2_{decay}(m_H)}{\Gamma_H}$

(2) $\frac{d\sigma^{H^*\rightarrow VV}_{off-shell}}{dm^2_{VV}} \propto g^2_{prod}(\hat{s})\,g^2_{decay}(\hat{s})$

H on-shell

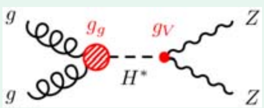
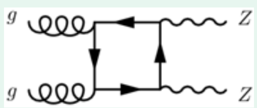
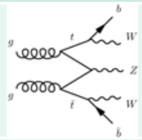
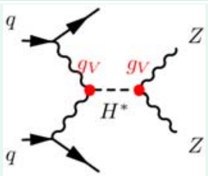
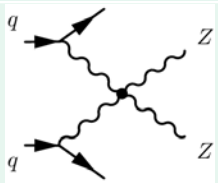
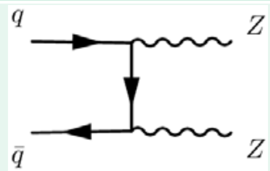
1 Z off shell

H off-shell: 10% contribution

Z on shell

→disentangle Γ_H

(if no BSM altering on, off- couplings differently for ggH (loop), HZZ)

	S	B	I	NI (non-interfering)
gg	$\lvert\mathcal{M}_S\rvert^2 \propto g^2_g g^2_V$	-	$2\mathcal{Re}(\mathcal{M}_S\mathcal{M}^*_B) \propto g_g g_V$<0	
				
qq (EW)	$\lvert\mathcal{M}\rvert^2 \propto g^4_V$		$2\mathcal{Re}(\mathcal{M}_S\mathcal{M}^*_B) \propto g^2_V$	
				

Unique scaling for each component→pdf=f(κ_g, κ_V)

(data-driven: Control Region)

$H^{*}\to ZZ\to 4l$ off-shell, Γ_H, NSBI

$$p(x|\mu^{\mathrm{ggF}}_{\text{off-shell}}, \mu^{\mathrm{EW}}_{\text{off-shell}}) = \frac{1}{\nu(\mu^{\mathrm{ggF}}_{\text{off-shell}}, \mu^{\mathrm{EW}}_{\text{off-shell}})} \times$$

$$\text{gg} \quad \Big[\mu^{\mathrm{ggF}}_{\text{off-shell}} \nu^{\mathrm{ggF}}_{\mathrm{S}} p^{\mathrm{ggF}}_{\mathrm{S}}(x) + \sqrt{\mu^{\mathrm{ggF}}_{\text{off-shell}}} \nu^{\mathrm{ggF}}_{\mathrm{I}} p^{\mathrm{ggF}}_{\mathrm{I}}(x) + \nu^{\mathrm{ggF}}_{\mathrm{B}} p^{\mathrm{ggF}}_{\mathrm{B}}(x) +$$

$$\text{qq} \quad \mu^{\mathrm{EW}}_{\text{off-shell}} \nu^{\mathrm{EW}}_{\mathrm{S}} p^{\mathrm{EW}}_{\mathrm{S}}(x) + \sqrt{\mu^{\mathrm{EW}}_{\text{off-shell}}} \nu^{\mathrm{EW}}_{\mathrm{I}} p^{\mathrm{EW}}_{\mathrm{I}}(x) + \nu^{\mathrm{EW}}_{\mathrm{B}} p^{\mathrm{EW}}_{\mathrm{B}}(x) + \nu_{\mathrm{NI}} p_{\mathrm{NI}}(x) \Big]$$

(data-driven: Control Region)

gg : SBI generated: deduce interference term

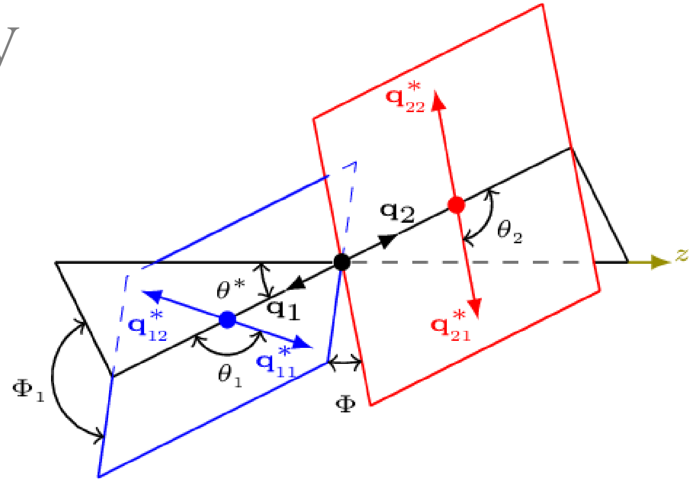
EW: can’t generate off-shell signal only

→generation w/ various signal strength→parametrise from linear algebra

Γ_H with $H^* \rightarrow ZZ \rightarrow 4l$

- **Selection**

$\geq$4 leptons (e, μ), p_T 3 leading ones: $\geq$20, 15, 10 GeV
Not on-shell: 180<m_{4l}<2000 GeV
Lepton quadruplet: 2 OS, SF dilepton pairs.
If ambiguity: choose closest to m_Z
Z_1: closest to m_Z
event: 14 observables
+preselection: cut multi-class NN



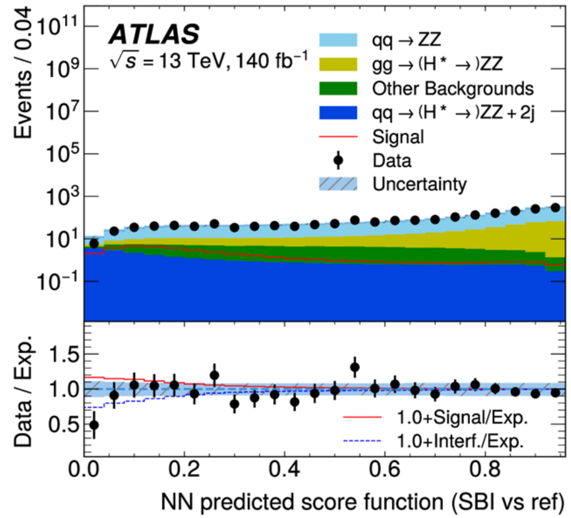
- **Neural Simulation-Based Inference (NSBI)**

Builds per-event likelihood ratio using NN from 14 observables optimally sensitive to any value of μ
Binned: events inside indistinguishable: loss stat power.
Increase dimensionality histogram: pb curse dimensionality
→better approximation of exact likelihood ratio

NSBI model

NN-estimated pdf $$\frac{p(x|\mu,\theta)}{p_{\mathrm{ref}}(x)} = \frac{1}{\nu(\mu,\theta)} \sum_{\mathrm{processes}\ X} f_X(\mu,\theta)\, \nu_X \boxed{\frac{p_X(x)}{p_{\mathrm{ref}}(x)}}$$

Reweight for factor for ratio wrt $\mu_{\text{off-shell}}$=1



Γ_H with $H^* \to ZZ \to 4l$

$Z_{obs}=2.5$ ($Z_{exp}=1.3$), $\mu_{off\text{-}shell}=0.87^{+0.75}_{-0.54}$ (exp: $1.00^{+1.04}_{-0.95}$)

Combination w/ $2l2\nu$ channel: $Z_{obs}=3.7$ ($Z_{exp}=2.4$)

$\mu_{off\text{-}shell}=1.06^{+0.62}_{-0.45}$ (exp: $1.00^{+0.83}_{-0.83}$)

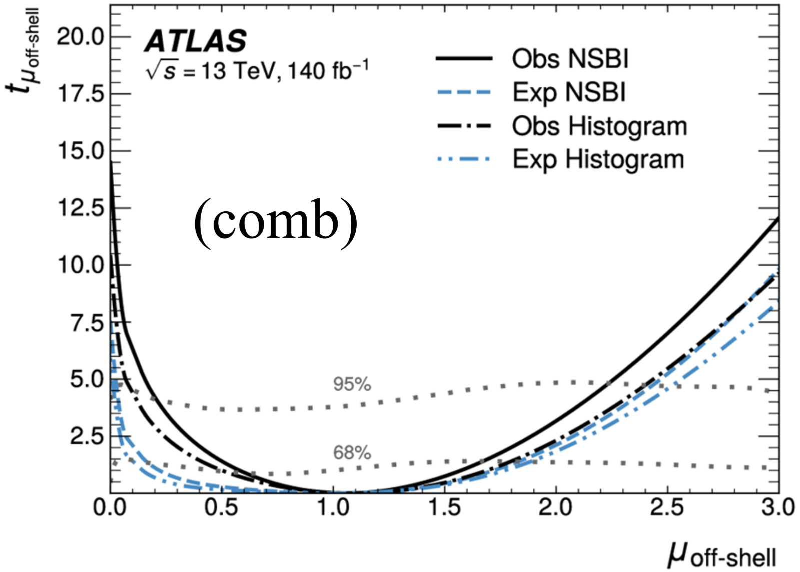
→evidence off-shell (already in past)

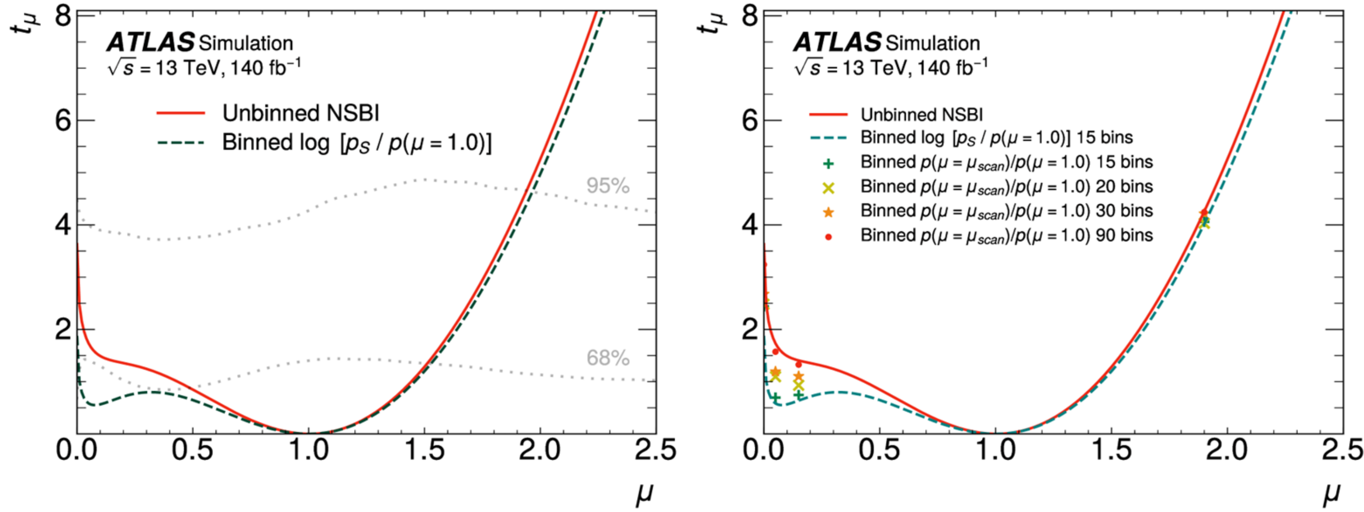
+κ framework results

$$\mu^{ggF}_{off-shell} = \kappa^2_{g,off-shell}\,\kappa^2_{V,off-shell}$$

$$\mu^{EW}_{off-shell} = \kappa^4_{V,off-shell}$$

CERN-EP-2024-305





Combination w/ on-shell $H \to ZZ \to 4l$

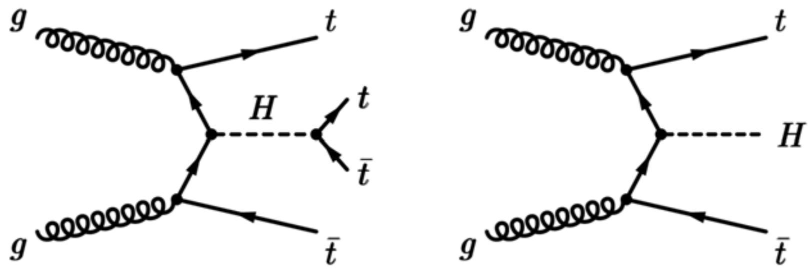
$\Gamma_H=4.3^{+2.7}_{-1.9}$ MeV (exp: $\Gamma_H=4.1^{+3.5}_{-3.4}$ MeV)

$H^* \rightarrow$ tttt off-shell, Γ_H

ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, CERN-EP-2023-055, March 2023

One could instead prob off-shell Higgs at tt kin. threshold
No more rely on ggH, HZZ: rely on tree-level Htt coupling
(assume same Htt on-shell & off-shell)

off-shell on-shell



ttH dominates sensitivity,
but other prod modes considered
(many final states)

- Combination

Correlates sytematics when relevant
Parameterisation event rates: κ-framework

- Results (syst. dominated: theory)

95% CL upper limit on Γ_H
obs: 110xSM (450 MeV)
exp: 18xSM (75 MeV)
If ‘resolve’ loop:
obs: 160 MeV
exp: 55 MeV

Much less sensitivity than $H \rightarrow ZZ$:
degeneracy of some κ (eg κ_W)

VH, H→bb, H→cc

Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1},
CERN-EP-2024-237

- Selection: complex

b-jet correction: σ ↓ up to 40 % (f(categ))
Flavour tagging: D^{b}_{DL1r} discriminant 70% WP
D^{c}_{DL1r} discriminant 45% WP

- Categories: V(νν/lν/ll) [suppr. multijets], #b, #c jets, p_T^V, +(resolved: #jets)

p_T^V>75 GeV (1, 2 leptons), >150 GeV (0 lepton)

-p_T^V<400 GeV: resolved: small-R jets (b & c), =2 b-jets, ≥1 c-jet, 0 b-jet
m_H>50 GeV, $\Delta R(j_1, j_2)<\pi$
p_T leading jet>45 GeV
CR for c-category

-p_T^V≥400 GeV: boosted: large R-jets (b only)
m_J>50 GeV, ≥2 matched track-jets, (H_{bb}: =2 b-jets)

- Final DV: BDTs

- Validation: VZ (Z_{obs}>5)

VH, H→bb, H→cc

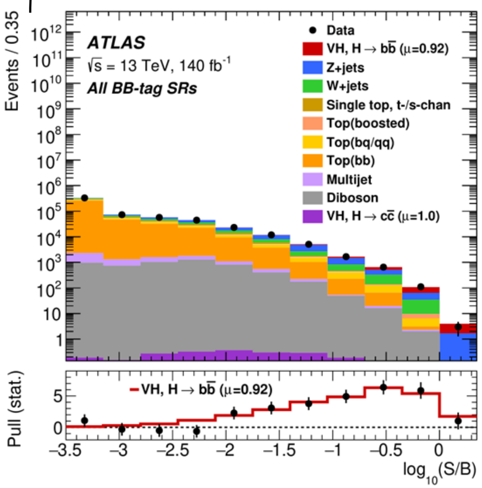
Run 2, √s=13 TeV, L=140 fb⁻¹, CERN-EP-2024-237, October 2024

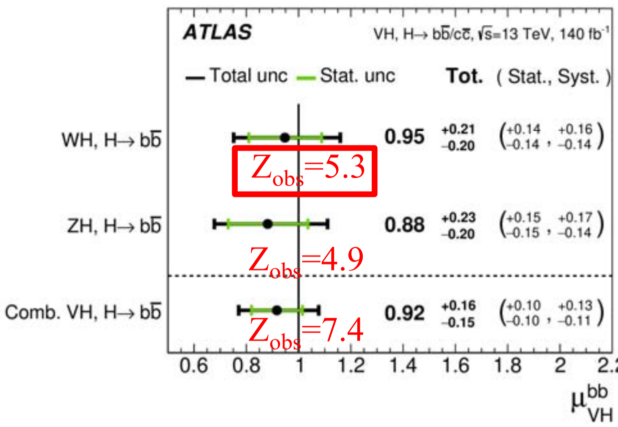
- Complex selection

b-jet correction: σ_{mH} ↓ up to 40 % (f(categ))
Flavour tagging: DL1R: b: 70%, c: 45%
Categories: V(νν/lν/ll), #b, #c, #light jets, p_T^V (resolved, boosted)
Control Regions + validation analysis: VZ (Z_{obs}>5)
Final DV: BDTs

- Results

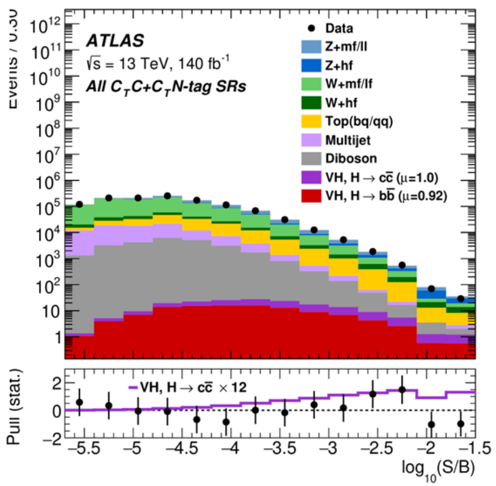
H→bb

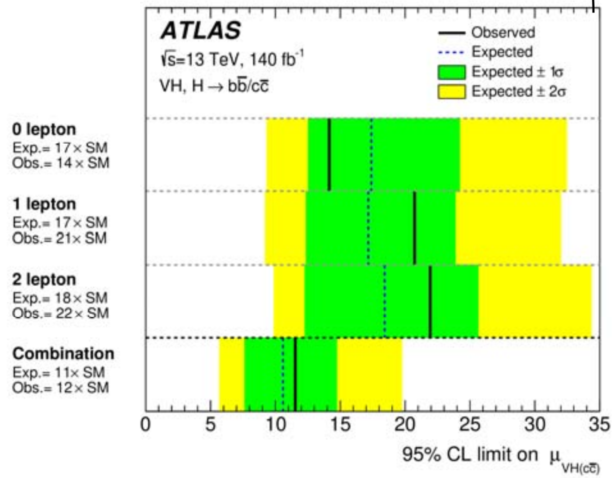




Z_{obs}=5.3
Z_{obs}=4.9
Z_{obs}=7.4

H→cc





First observation of WH, H→bb

VH(cc) 95% CL limit: 11.5xSM

Improvement previous analysis: better reco, calibration l, jets
Improved flavour tagging b & c. Extended acceptance p_T^V<150 GeV, Improved MVA

VH, H→bb, H→cc

- VH interpreted in κ-framework

$$\mu_{VH}^{bb} = \frac{\kappa_b^2}{1 + B_{Hbb}^{\mathrm{SM}}(\kappa_b^2 - 1) + B_{Hcc}^{\mathrm{SM}}(\kappa_c^2 - 1)}$$

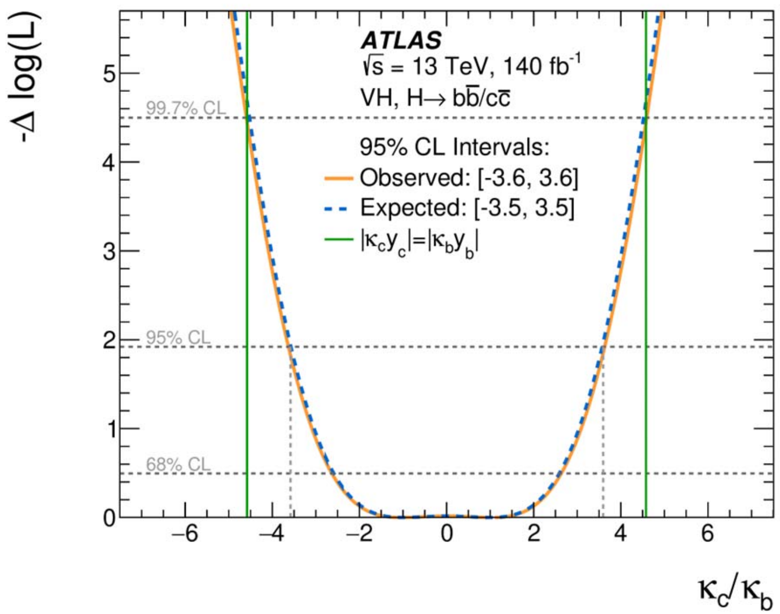
$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{Hbb}^{\mathrm{SM}}(\kappa_b^2 - 1) + B_{Hcc}^{\mathrm{SM}}(\kappa_c^2 - 1)}$$

$|\kappa_c/\kappa_b|$: no assumption on Γ_H

95% CL limit

obs: 3.6

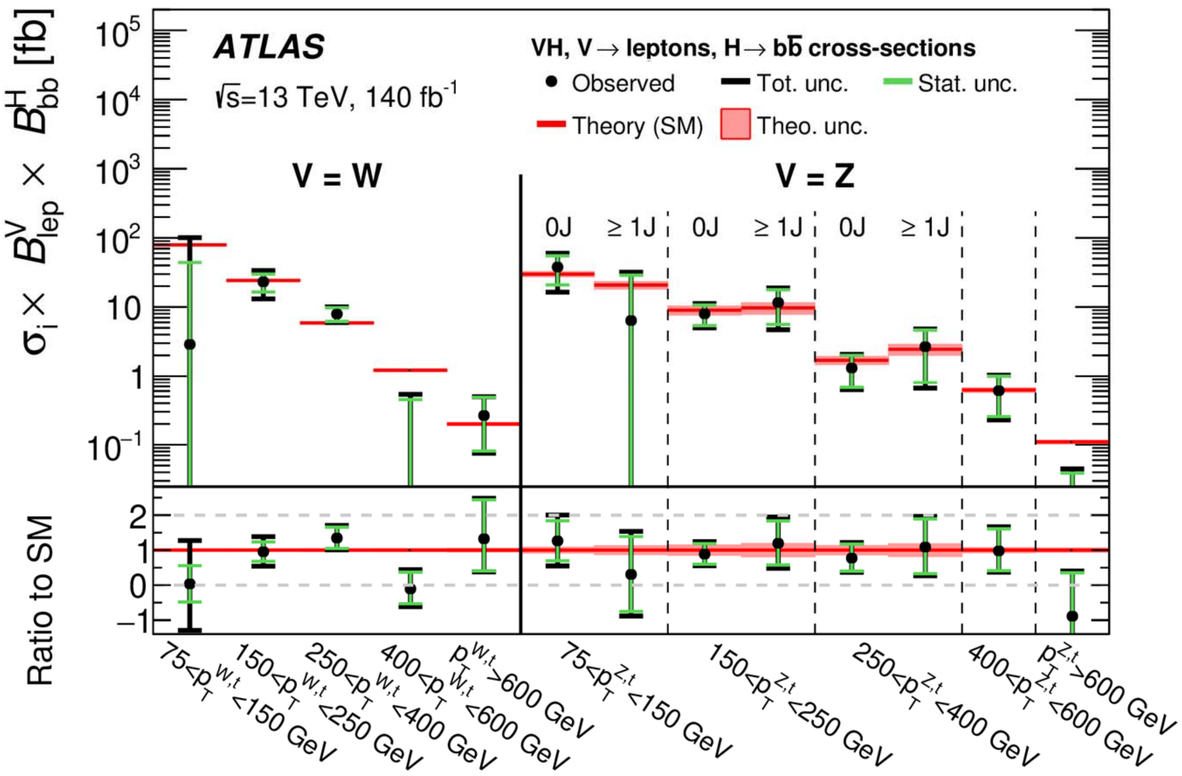
exp: 3.5



Confirming non-universality of Hqq coupling: $Y_{hcc} < Y_{Hbb}$

- STXS H→bb, 13 bins kinematic fiducial regions

Category mirroring it

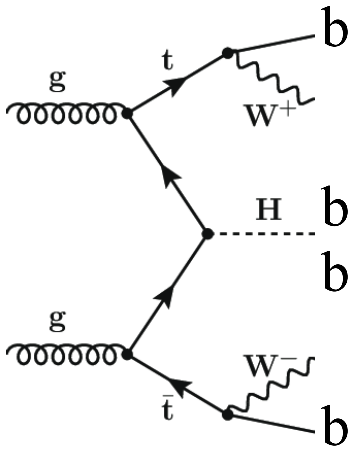


Dominated by stat uncertainty

ttH, H→bb, 1 or 2 leptons

ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, CERN-EP-2024-194

- Complex final state: e, μ, jets, b-jets



Ingredients preselection (acceptance: 6.3% for ttH)

1-lepton	2-leptons channels
(resolved, boosted)	(resolved)
	OS
	if ee or μμ: m_{ll}>… (suppr. HF, DY)
	∉ m_Z±… (suppr. DY)

veto f(#τ_{had}): ⊥ ttH other decays

#jets, #b-jets

Lepton id & isolation (suppr. non-prompt, fake lepton)

- multiclass NN: defines SR, CR

Pairing jets-Higgs: second NN: reconstruct p_T^H for STXS

- Background

Primary: tt+jets: MC+data-driven corrections

Secondary: 1-t, ttW, ttZ, tttt, V+jets, VV: MC

Non-prompt: data & MC: f(#leptons)

ttH, H→bb, 1 or 2 leptons

1-lepton: =1-lepton, resolved/boosted

resolved: ≥5 jets w/ ≥3 b-jets (70% WP)

boosted: ≥1 large-R jet, ≥4 small-R jets (including large one) w/ ≥3 b-jets (85% WP)

2-lepton: =2-leptons, OS

ee: 2nd lepton p_T>15 GeV

eμ, μμ: 2nd lepton p_T>10 GeV

ee, μμ: m_{ll}>15 GeV (suppr. HF, DY),∉ m_Z± 8 GeV (suppr. DY)

≥3 b-jets (85% WP) w/ ≥2 b-jets (70% WP)

≥1 lepton p_T>27 GeV

veto f(#τ_{had}): ⊥ ttH other decays

Lepton id & isolation (suppr. non-prompt, fake lepton)

SR, CR: output of multiclass NN

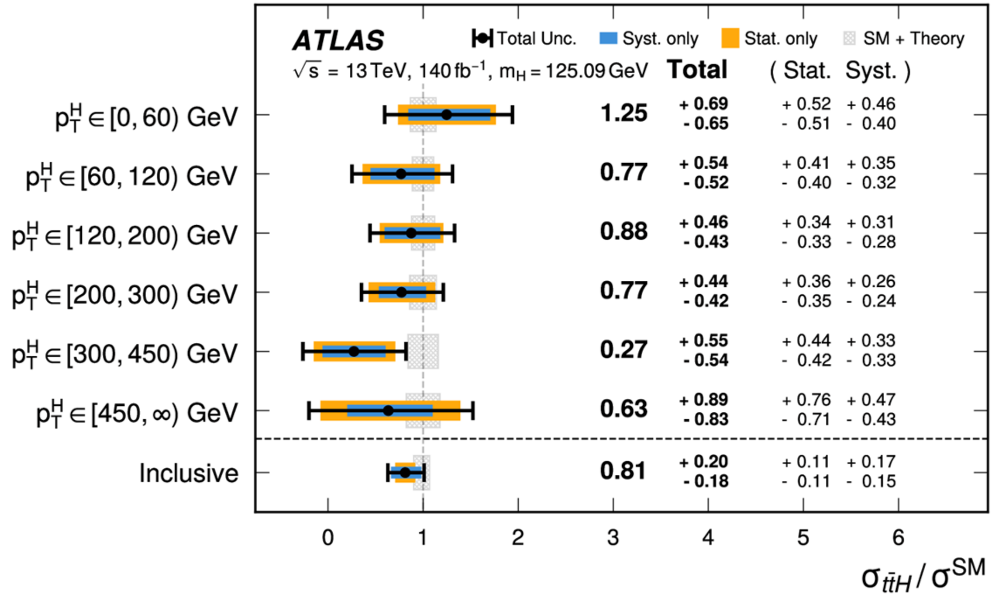
Pairing jets-Higgs: second NN: reoncstuct p_T^H for STXS

ttH, H→bb, 1 or 2 leptons

- Results inclusive & STXS (bins p_T^H)

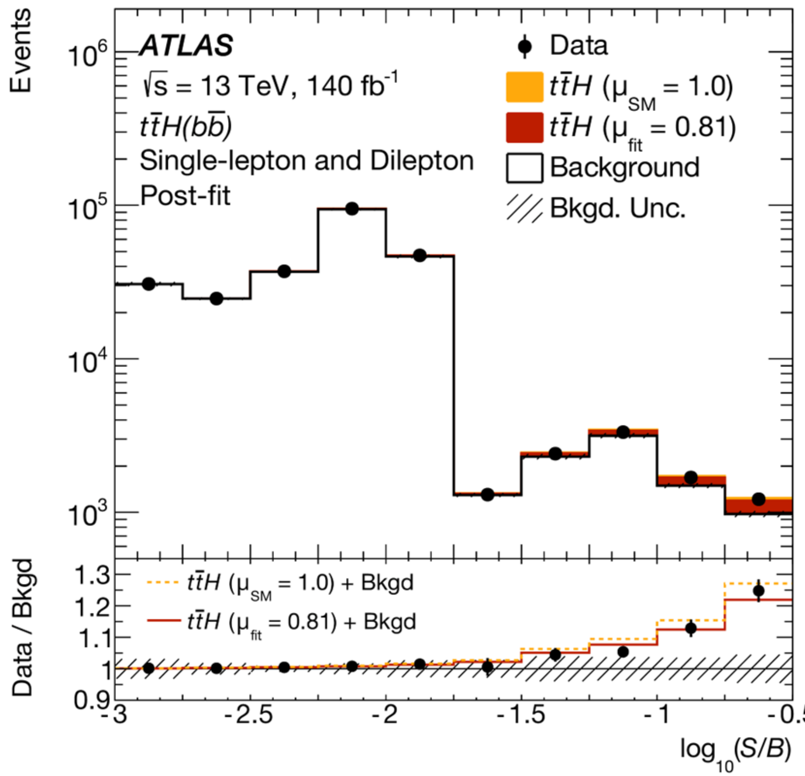
Z_{obs}=4.6 (Z_{exp}=5.4)

$$\mu_{ttH} = 0.81 \pm 0.11\,(stat)^{+0.20}_{-0.16}\,(syst)$$



Most precise ttH cross-section measurement in a single decay channel, inclusively and in each p_T^H

- Yield=f(log_{10}(S/B))



Legacy: main improvements: Increased acceptance

Advanced b-jet identification

Better CRs from multiclass neural network

$H \rightarrow \tau\tau$, diff. measurement

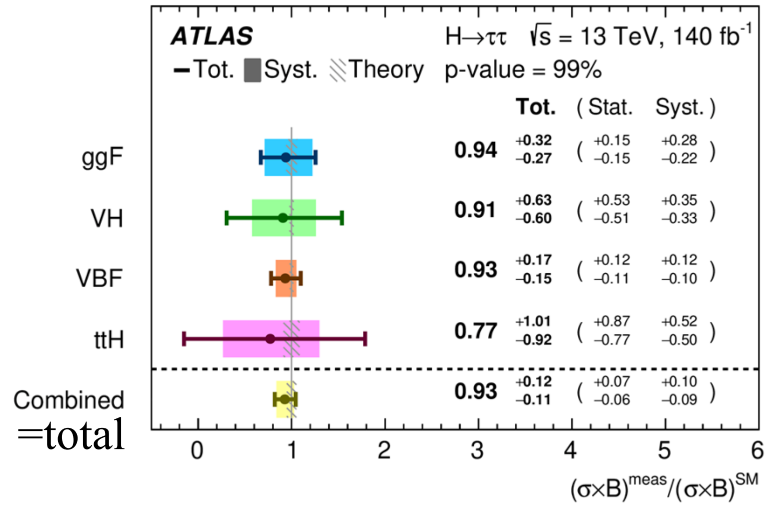
Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1}, CERN-EP-2024-198

$\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_e\tau_\mu$ (different flavour)
Fake objects: data-driven measurements
Missing Mass Calculator: likelihood for $m_{\tau\tau}$

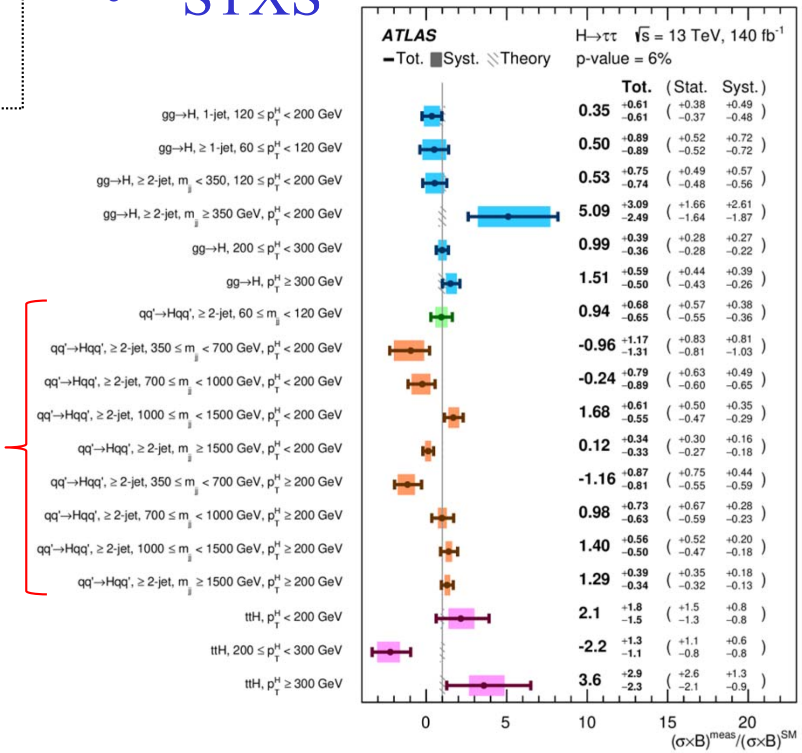
- Categorisation for STXS (and VBF for dσ/dX)

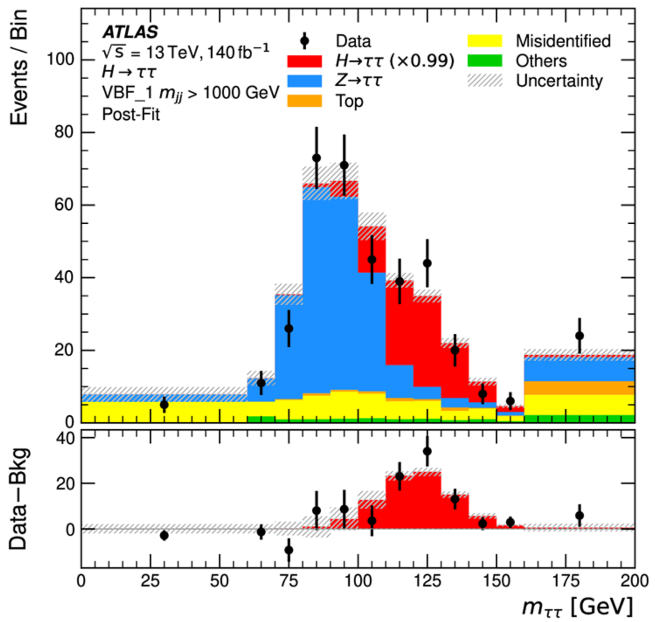
-VBF: 2 high-p_T jets large $|\Delta\eta_{jj}|$, m_{jj}
-tt(0l)H→$\tau_{had}\tau_{had}$: ≥6 jets (≥1 b-tagged) or ≥5 jets (≥2 b-tagged) subsplit: BDT
-V(had)H: 60<m_{jj}<120 GeV, $p_T^{\text{sub-lead j}}$>30 GeV+BDT
-Boost (ggF): p_T^H>100 GeV, subsplit by kinematics

- Production modes



- STXS





First VBF measurement in higher-p_T^H and most precise for lower p_T^H

H→ττ, diff. measurement

- dσ/dX w/ VBF selection

f_j: out-of-acceptance : #events pass fiducial & reco / #events ass reco level selection
M: migration matrix, Prob(reco bin j | truth bin i)⇔M^{-1}: Prob(truth bin i | reco bin j)
ε_i: #events in fiducial region and rec / #events in fiducial region

$$\sigma_i^{\text{fid}} = \frac{1}{\mathcal{L}\epsilon_i} \sum_j \mathcal{M}_{ij}^{-1} f_j \left(N_j^{\text{data}} - N_j^{\text{bkg}}\right)$$

truth bin (i)

rec bin (j)

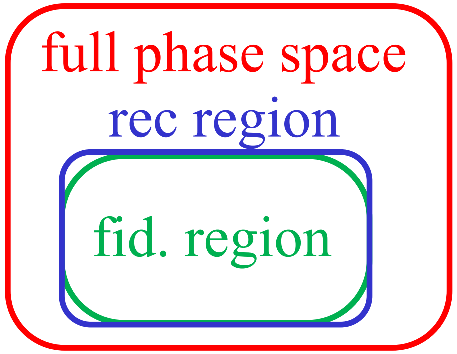
#events S in rec bin j ①

#events S in rec bin j in fid. region ②

#events S in truth bin i in rec bin j ③

#events S in truth bin i in all rec-level bins ④

#events S in truth bin i in fiducial region (unfolding) ⑤

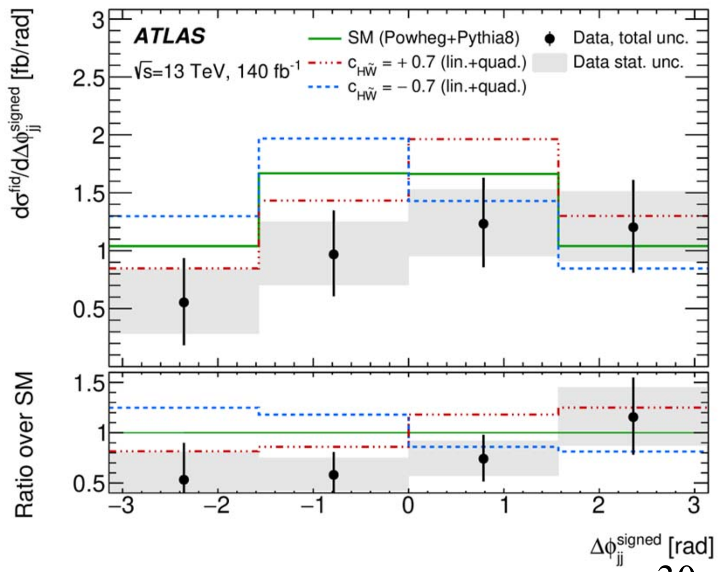


rec bins: mirror fiducial regions of STXS

Fiducial phase space (83% VBF)

$p_T(j_0)$, p_T^H, $\Delta f_{jj}^{\text{signed}}$, $\Delta\phi_{jj}^{\text{signed}}$
Precision: 30-50%

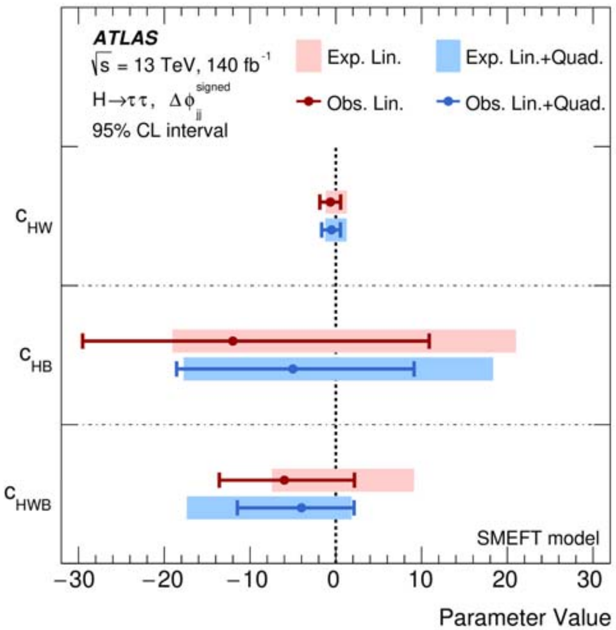
$\Delta\phi_{jj}^{\text{signed}}$ sensitive to the VBF production vertex
Interpreted in SMEFT. Probe 3 Wilson coefficients and CP-odd counterparts.
Strongest constraint on CP-odd $c_{H\widetilde{W}}$



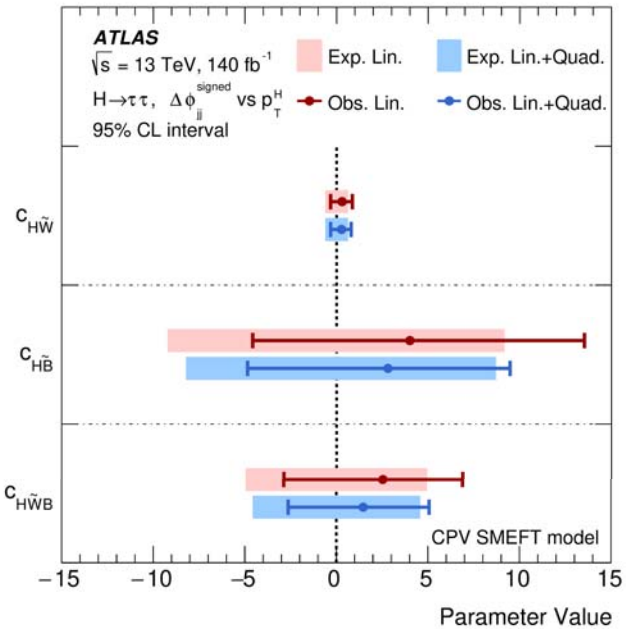
$H \rightarrow \tau\tau$, diff. measurement

- Wilson coefficients: CL intervals

CP-even



CP-odd



Strongest constraint on CP-odd $c_{H\widetilde{W}}$

Higgs combination (STXS, dσ/dX) EFT interpretation

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=139 fb^{-1}, JHEP 11 (2024) 097

- Model independent: SMEFT, Warsaw basis

-Higher-dim operators built from SM fields (CP-even operators [odd: too small effect])
-UV-unsafe but cut-off Λ (1 TeV, but rescale possible)
-top flavour symmetry: 2 first generations quarks treated similarly

- Inputs

-σ prod. modes (STXS-0), STXS-1.2: H→γγ, H→ZZ*→4l, H→bb, H→ττ, H→WW*→eνμν, H→Zγ, H→μμ
-$d\sigma/dp_T^H$: H→γγ, H→ZZ*→4l
Reparameterisation=f(c_i) Wilson coefficient
MadGraph, SMEFTSim

- Cross-section x BR: parametrized

$$(\sigma\times\mathcal{B})^{i,k',H\to X}_{\mathrm{SMEFT}} = (\sigma\times\mathcal{B})^{i,k',H\to X}_{\mathrm{SM,((N)N)NLO}} \times \left(\frac{1+\sum_j \left(A_j^{\sigma_{i,k'}} + A_j^{\Gamma^{H\to X}}\right) c_j + O\left(\Lambda^{-4}\right)}{1+\sum_j A_j^{\Gamma^H} c_j + O\left(\Lambda^{-4}\right)} \right)$$

no subsequent Taylor expansion for decay (bias for high c)

Narrow width→factorize: independent prod x decay
Linear in c_i ($\sim\Lambda^{-2}$) or lin+quadratic in c_i ($\sim\Lambda^{-4}$)
Comparison: qualitative info on validity neglecting dim-8

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)}$$

Higgs combination (STXS, dσ/dX) EFT interpretation

- eff x accept: not parametrized

STXS fine granularity=restricted kinematic region : acceptance ≈ insensitive to EFT
Assumed theoretical systematic cover possible modification

- Decay: f(EFT) (no restriction to kinematic region)

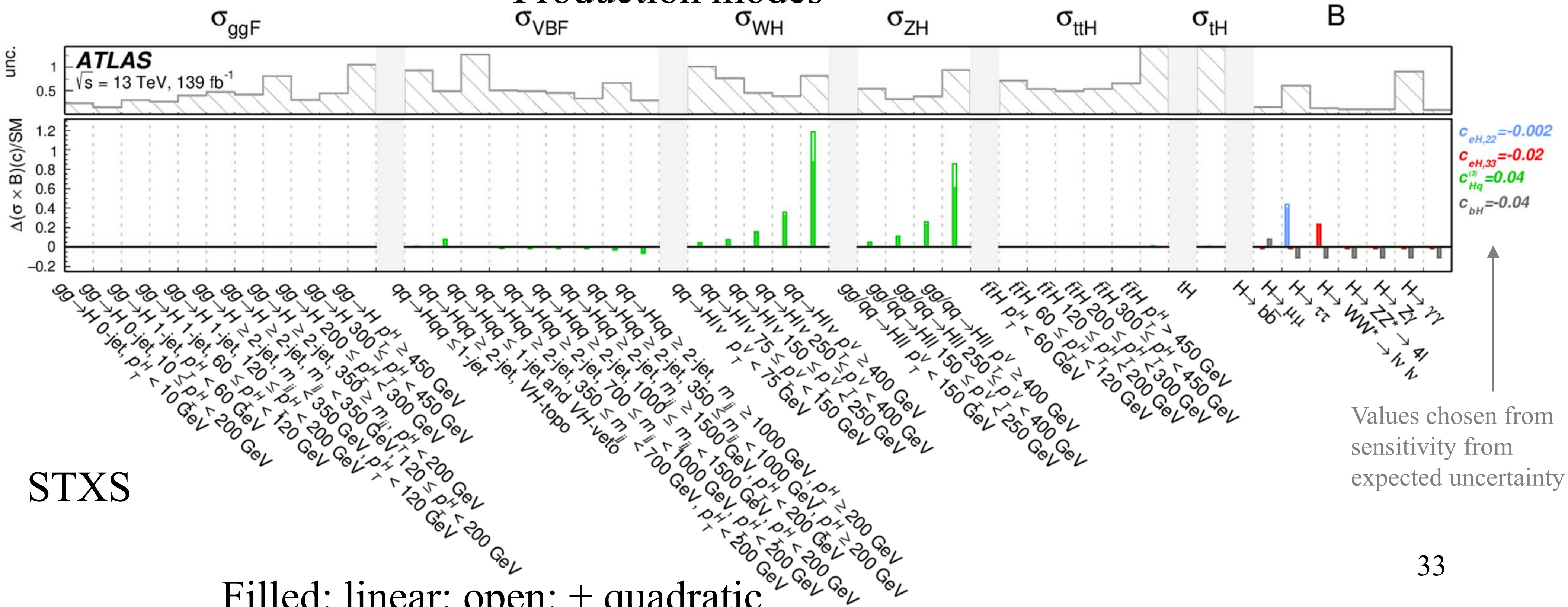
2 bodies: small effect: small. >2 bodies decays : parametrisation

- Shape final discriminant: negligible effect on (eg $m_{\gamma\gamma}$ for H→γγ), else parameterised

Production modes

$\Delta\sigma_{STXS}$

rel imp. c_i



Values chosen from sensitivity from expected uncertainty

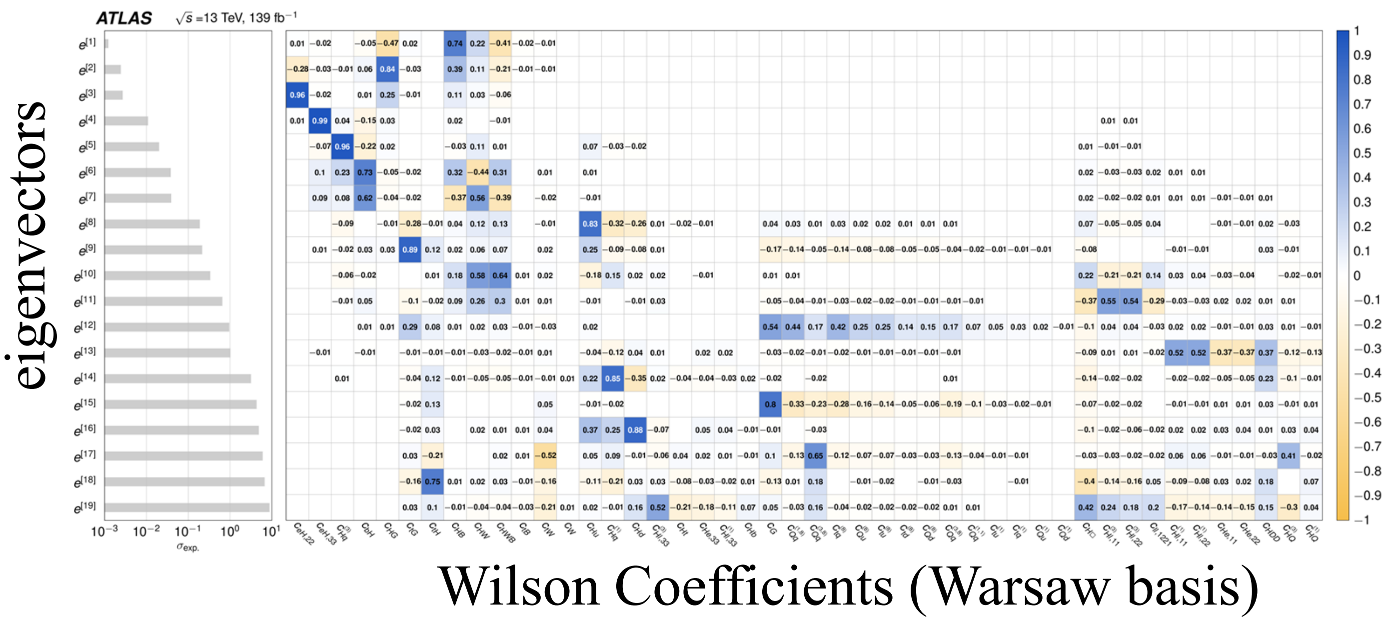
STXS

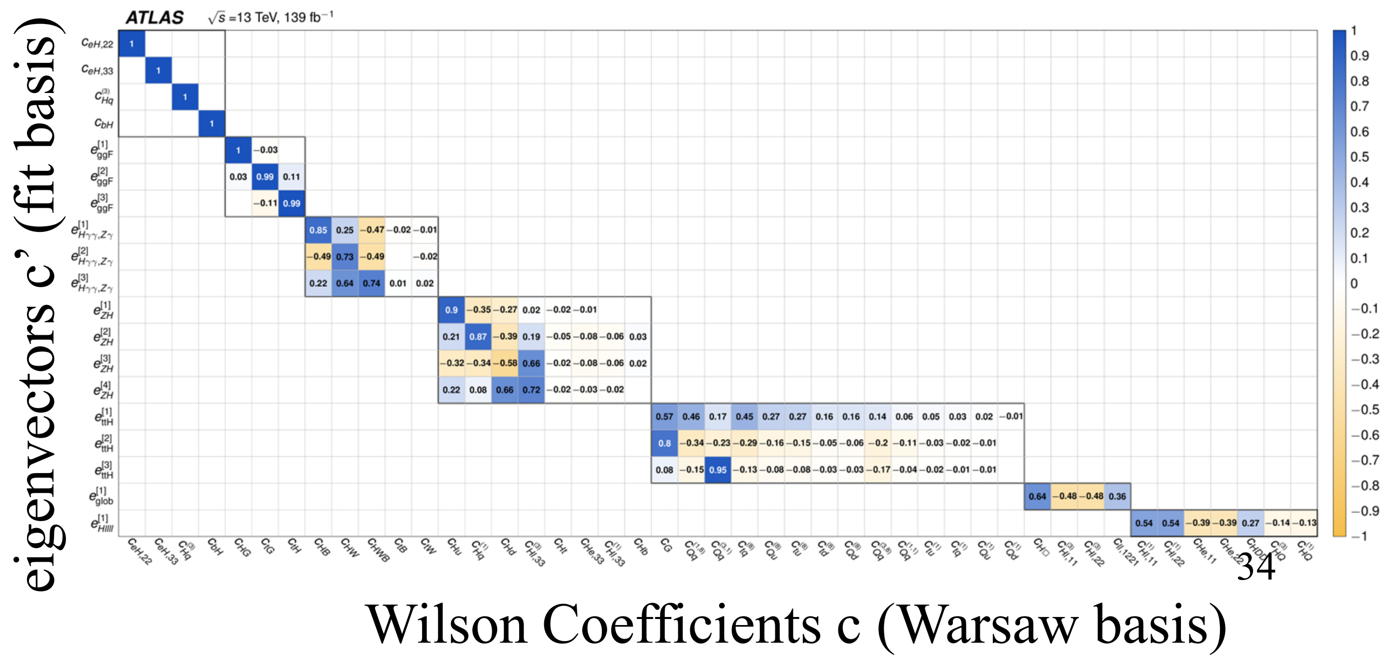
Filled: linear; open: + quadratic

Higgs combination (STXS, dσ/dX) EFT interpretation

Even though top symmetry: too many operators, and correlations

Eigenvectors from V_{SMEFT}^{-1}





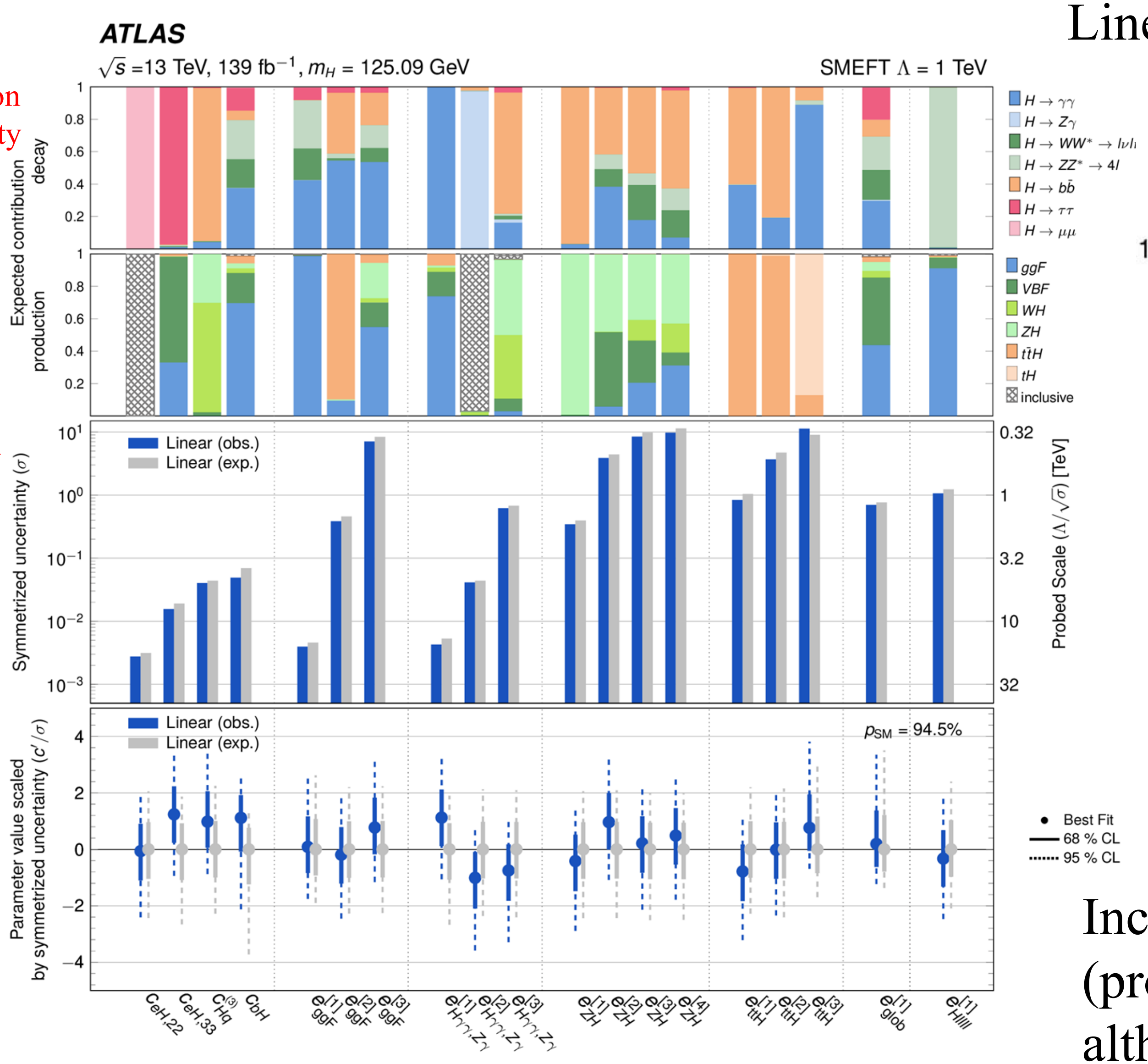
Higgs combination (STXS, dσ/dX) EFT interpretation

- Results STXS (here linear)

Contribution to sensitivity of c_i

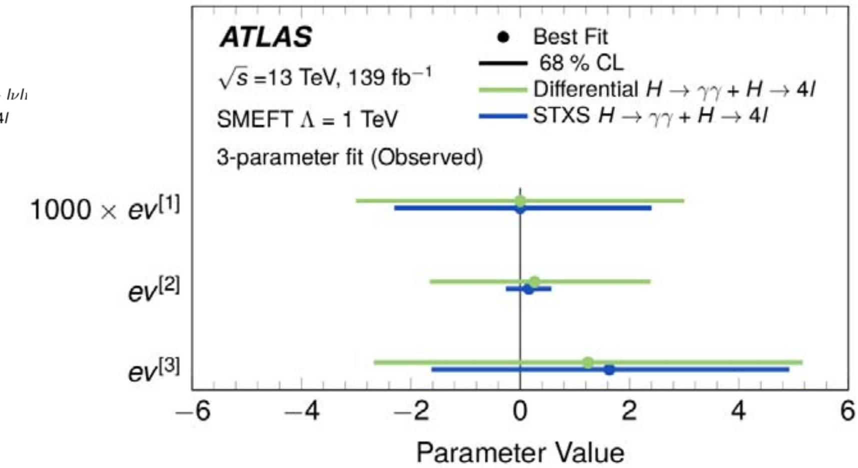
uncertainty

pull



- Results $d\sigma/dp_T^H$, H→γγ, H→4l

Linear only; other eigenvectors



obs

exp

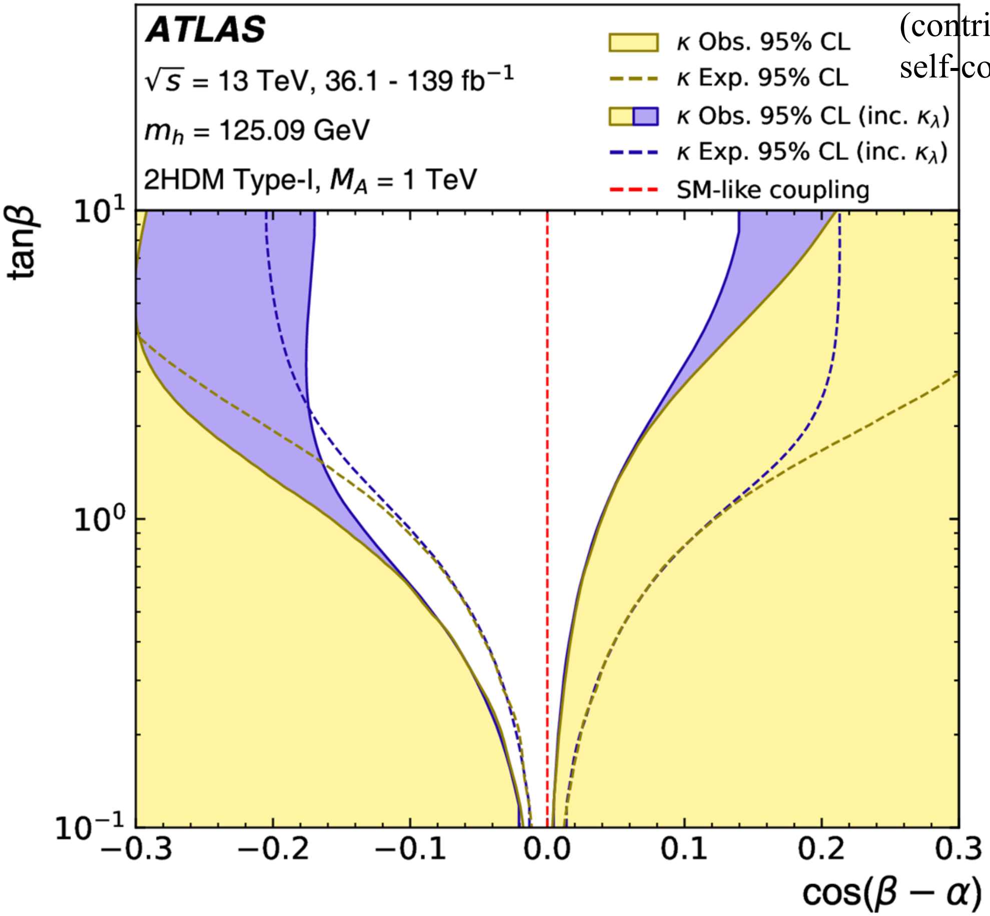
Increased sensitivity from STXS (production modes, many variables, although lower granularity than p_T^H)

Higgs combination (STXS, dσ/dX) EFT interpretation

UV-complete BSM

- 2HDM

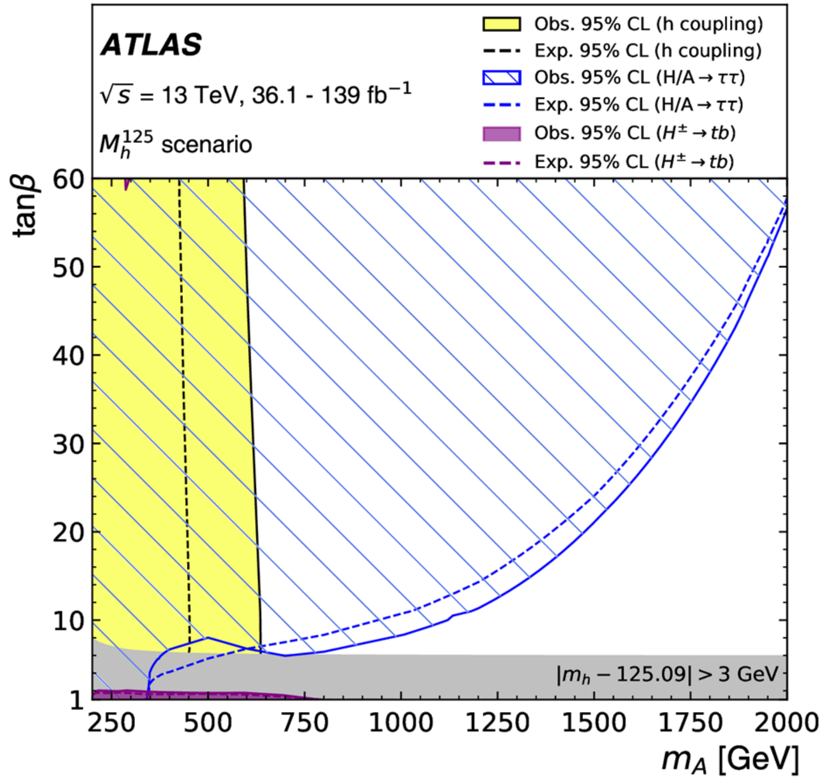
Add VH x H→WW*, VH, ttH x H→multileptons
from κ (no inv., und. Higgs), from EFT
Example Type I from κ
Good agreement in regions w/ dim-8 negligeable



(contrib Higgs self-coupling)

- MSSM, 8 benchmarks

Example : m_h^{125}



H→Zγ

ATLAS+CMS, Run 2, √s=13 TeV, L=139+138 fb^{-1}, PRL 132 (2024) 021803, September 2023

- Rare (HR=1.5×10^{-3}), loop diagrams: sensitive to BSM

Z→ll [e or μ], m_{ll}>50 GeV: clean signature, good mass resolution

γ: identified/isolated

$m_{Z\gamma}$: improve resolution: FSR correction momentum μ+ kinematic fit m_{ll}

Categories=f(kinematic features, process, BDT)

Dominant bkg : Drell-Yan+jets

- Experimental systematics: uncorrelated

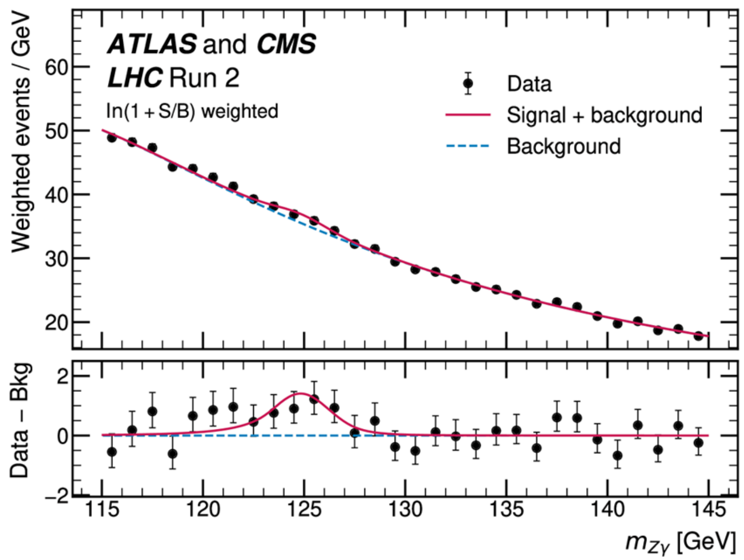
(some could be correlated but << uncorrelated ones)

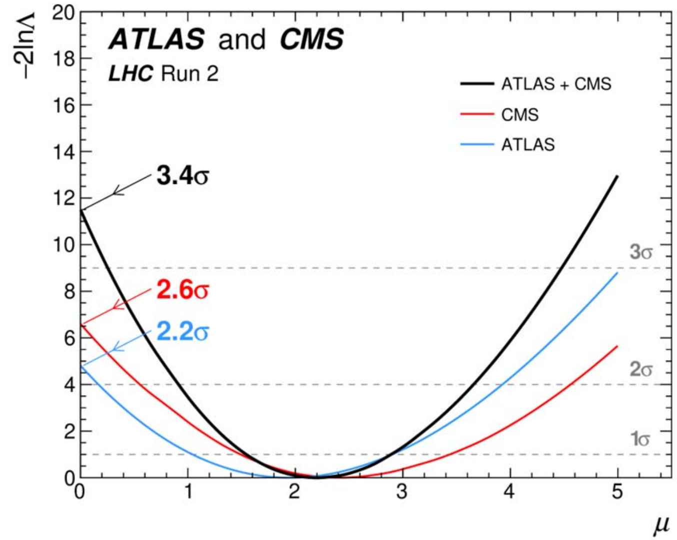
- First evidence for H→Zγ

Z_{obs}=3.4 (Z_{exp}=1.6)

ATLAS: obs: 2.2 (exp: 1.2)

CMS: obs: 2.6 (exp: 1.1)



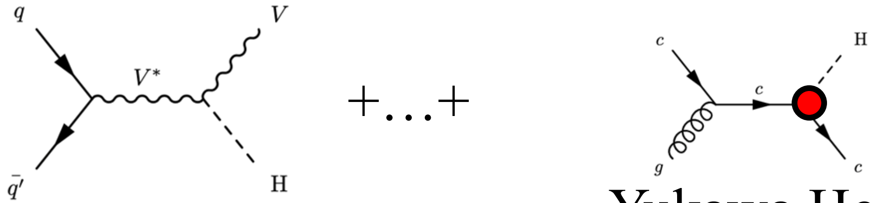


$\mu^{obs}=2.0^{+1.0}_{-0.9}$

$\mu^{exp}=1.0 \pm 0.9$

$H \rightarrow \gamma\gamma + c$

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1},
CERN-EP-2024-175, July 2024



Yukawa Hcc
(1% only of whole process)

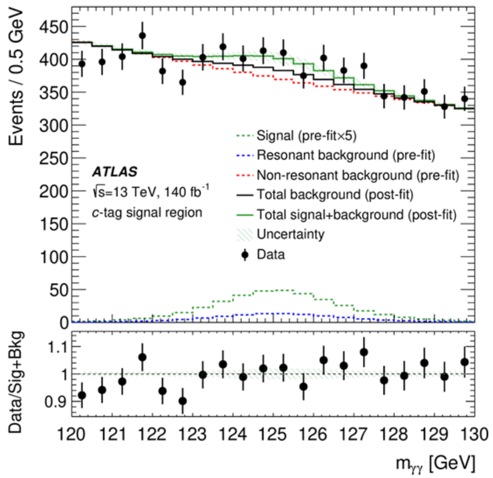
- Selection

Photons: high p_T, identified/isolated
$m_{\gamma\gamma} \in [105 ; 160]$ GeV
Signal Regions ($m_{\gamma\gamma} \in [120 ; 130]$ GeV)
c-tag SR: ≥1 c-jet (DL1r : prob b, c, l)
non c-tag SR: due to low eff c-tag

- Background

γγ+j, resonant H production (!) (Gaussian Process Regression)
modelisation cont.: GPR*, extrapol. data from sideband

- Binned likelihood fit: $m_{\gamma\gamma}$



- Significance

Z_{obs}=1.7
Z_{exp}=1.0

- 95% CL upper limit

obs: 10.4 pb
exp: 8.6 pb
exp c-tag: 9.6 pb
non-ctag: 14 pb

- Measurement σ

obs: 5.2 ± 3.0 pb
exp: 2.9 ± 2.8 pb
(dominated by stat uncertainty)

First search of this production

Rare decay $H \rightarrow D^{*}\gamma$

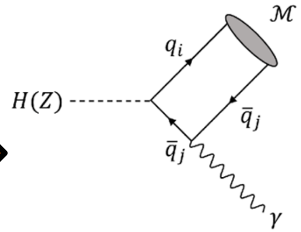
ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=136.3 fb^{-1}, PLB 855 (2024) 138762, Feb. 2024

$H \rightarrow D^{*}(D^0\pi^0, D^0\gamma)\gamma$, D^0: $c\bar{u}$ (and conjugate)

$D^0 \rightarrow K^-\pi^+$

Rare: SM: loop contributions, BR=7×10^{-27}

Probe flavour-violating coupling: BSM



- Selection:

meson+γ back-to-back: loose cut $\Delta\phi(D^0, \gamma) > \pi/2$

soft π^0 and γ not reconstructed (no loss efficiency)

γ: identified, isolated

D^0: charged hadrons: ID tracks, OS

displaced vertex: $L_{xy}/\sigma_{Lxy} > 3$ (suppr. prompt vertices)

radius <15 mm (in beam pipe: suppr. multijets & interactions in detector material)

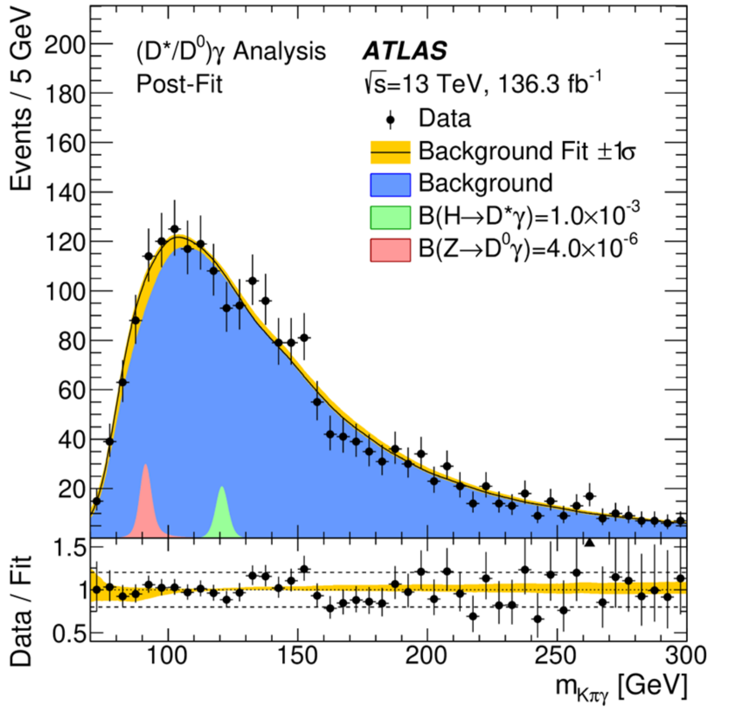
isolated (Σp_T ID tracks not from PV)<10% p_T meson

$m_{\mathcal{M}} \in [1800 ; 1930]$ MeV, $p_T^{\mathcal{M}} > 39$ GeV

- Background: multijets, γ+jets

non-parametric data-driven, very finely binned template

- Unbinned likelihood fit $m_{\mathcal{M}\gamma}$ ([70 ; 300] GeV)



- 95% UL on BR($H \rightarrow D^{*}\gamma$)

obs: 1.0×10^{-3}

exp: $1.2^{+0.5}_{-0.3} \times 10^{-3}$

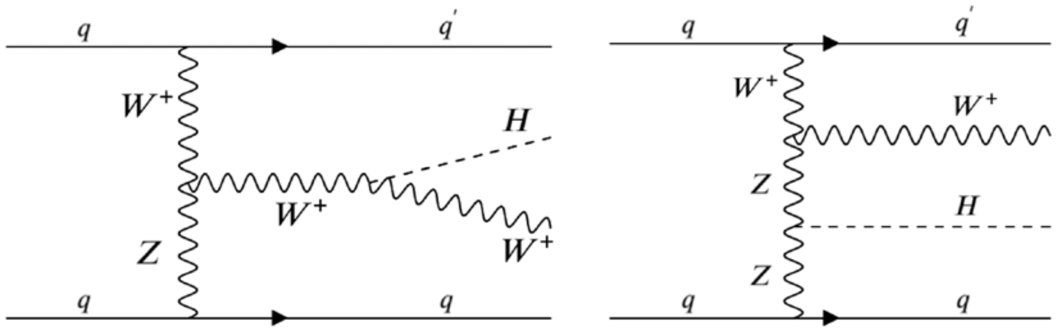
First limit set on this decay

VBF WH, H→bb, λ_{WZ}

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1},
PRL 133 (2024) 141801, Feb 2024

Gauge symmetry electroweak model broken by Higgs doublet, $\rho = \frac{m_W^2}{m_Z^2 cos^2\theta} = 1$

Experimentally valid at 1% level.
Still valid after radiative corrections: custodial symmetry to protect it
Test $\lambda_{WZ}=\kappa_W/\kappa_Z$: any deviation from 1⇔violation custodial symmetry
(isospin multiplet>doublet, eg some Georgi-Machacek)
VBF WH(bb) allow probes non quadratic terms. Destructive in SM, constructive if $\lambda_{WZ}<0$



2 b-jets, 2 jets , charged lepton, MET
2 analyses. binned likelihood fit: Poisson counting
Positive λ_{WZ} analysis: 95% CL limit on μ: obs: 9.0, exp: 8.7
Negative λ_{WZ} analysis: $\kappa_W<0$ excluded. $\kappa_Z<0$ excluded w/ Z>5

de Lima, Stolarski, arXiv:2404.10815: still allowed if ≥1 charged Higgs w/ mass<370 GeV

Cross-sections combination

Run 3, √s=13.6 TeV, L=29.0-31.4 fb^{-1}, CERN-EP-2023-114

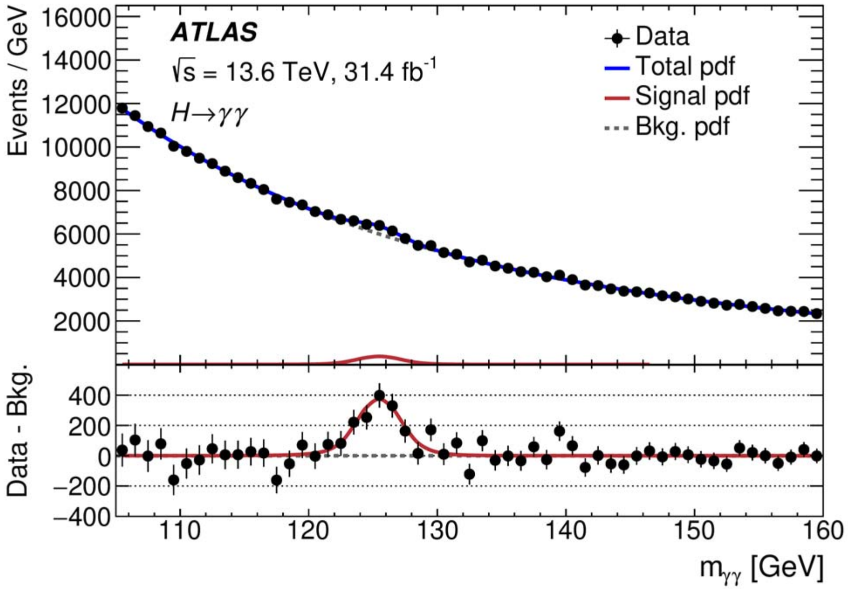
H→γγ+H→ZZ*→4l

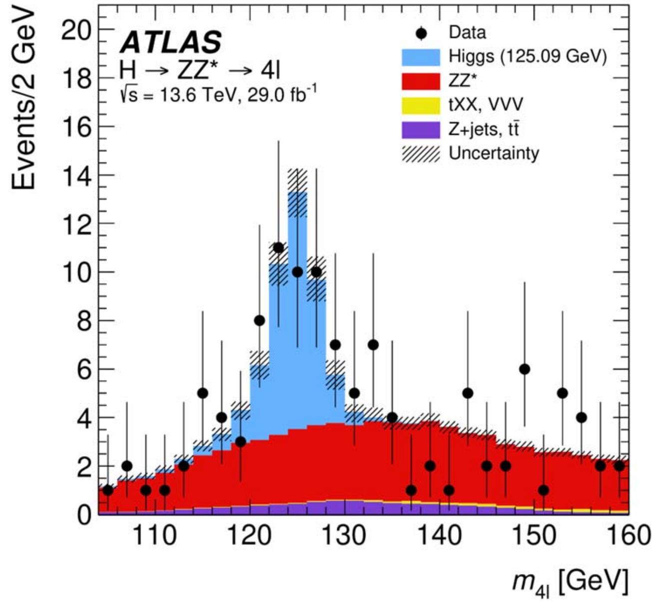
(note 'today', 183 fb^{-1} available)

Fiducial cross-sections

$\sigma_{fid}^{\gamma\gamma} = 76 \pm 11\ (stat)\ ^{+9}_{-7}\ (sys.)$

$\sigma_{fid}^{4l} = 2.80 \pm 0.70\ (stat)\ 0.21\ (sys.)$

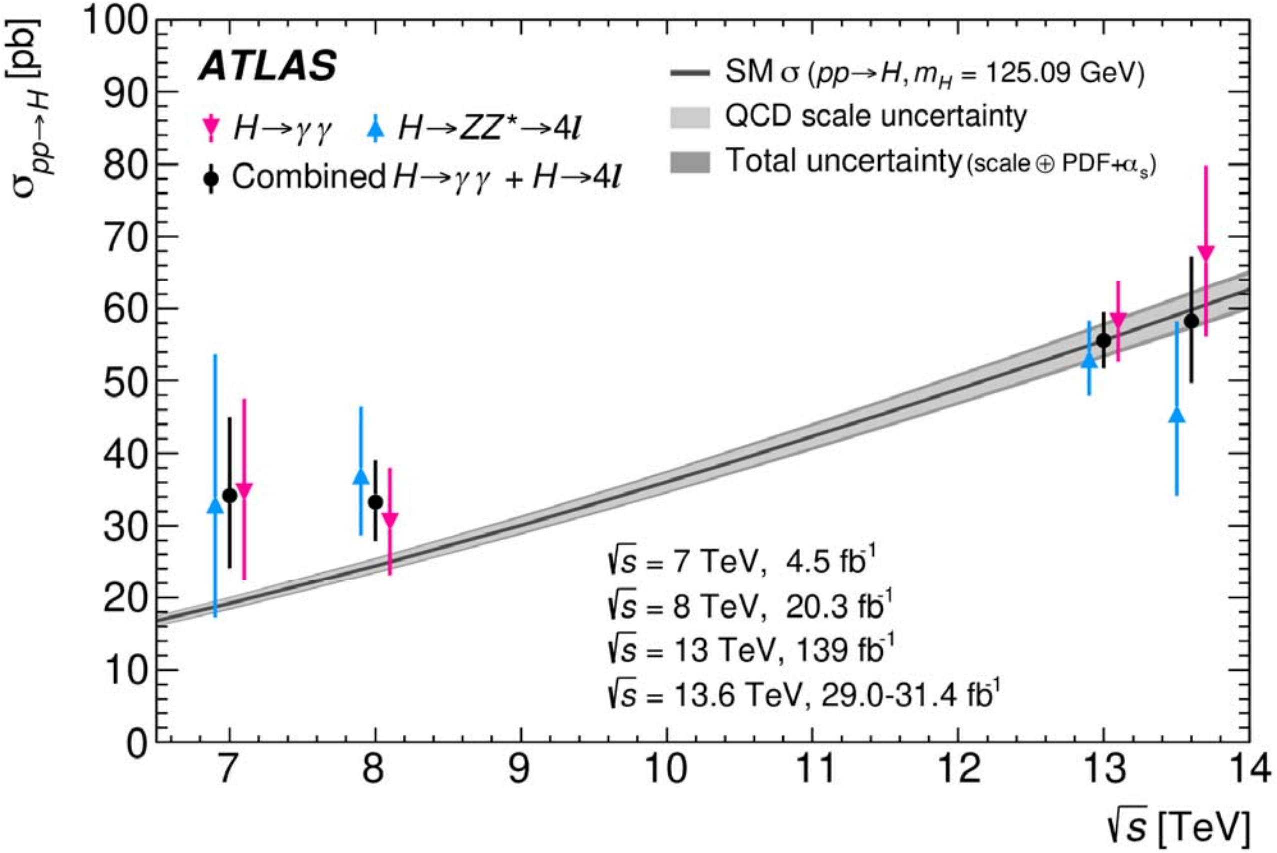




Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

Cross-sections combination

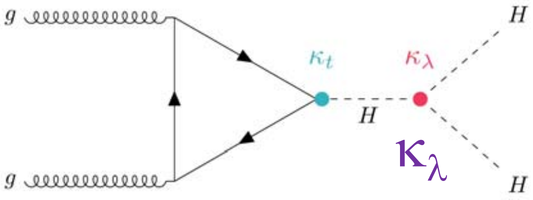


Excellent agreement w/ energy dependence
Dominated by stat. Uncertainty
(note ‘today’, 183 fb^{-1} available)

HH: dominant prod. modes

- **Non-resonant** (in the HH)

ggF



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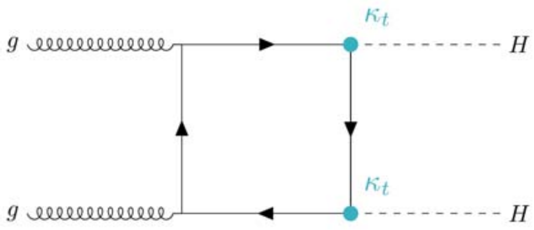
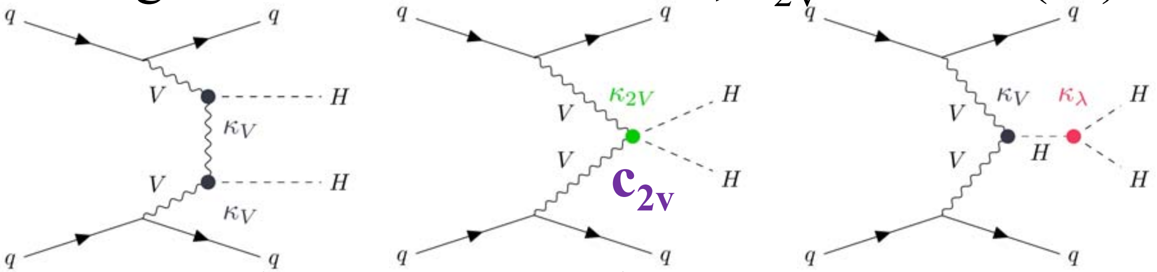
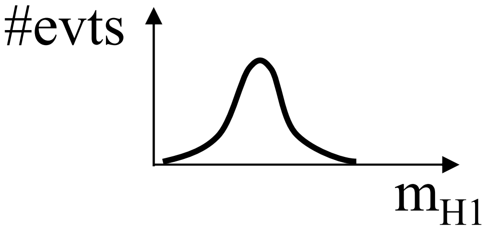


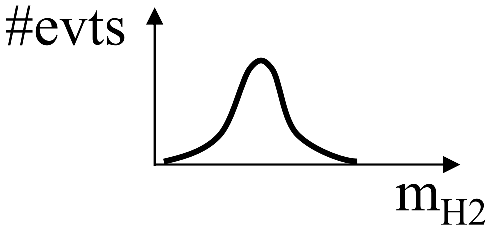
Divergences cancel out in SM ; $\kappa_{2V} \neq 1 \Leftrightarrow \sigma = f(\sqrt{s})$

VBF

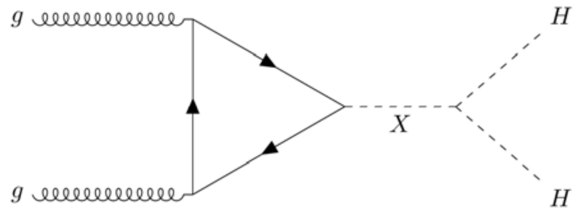


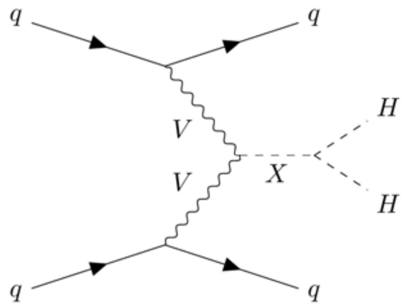
unique way to probe VVHH

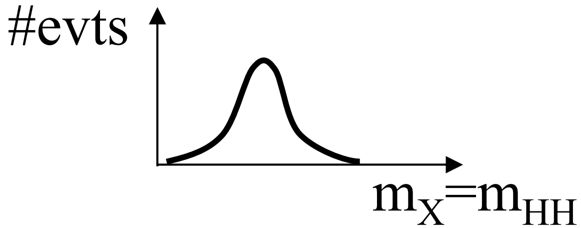




- **Resonant**







- **Resonant** J=0 (scalar), hMSSM, tan β=2 CP-even Higgs: X
  J=2, RS KK graviton G_{KK}, parameters: k: curvature WED,
  M_{Pl}: effective 4D Planck scale

X (S, G)→HH
X (S, G)→S'S'
X (S, G)→G'G'

Non-resonant HH Combination

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126-140 fb^{-1}, PRL 133 (2024) 101801, June 2024

- Channels

-bbbb resolved, boosted
-bb$\tau\tau$ 1 τ_{had} ⇔ ⊥ bbll+MET] Improved classifications
-bb$\gamma\gamma$
-multilepton: select bbZZ^*, VV^*VV^*, $VV^*\tau\tau$, $\tau\tau\tau\tau$, $\gamma\gamma VV^*$, $\gamma\gamma\tau\tau$
-bbll+MET: bb + (ZZ^*, WW^*, $\tau\tau$)→ll

Overlap data & MC:
<1% in SR⇔negligible

- Final DV: m_{HH}, $m_{\gamma\gamma}$, MVA=f(channel)

- Systematics & correlation scheme

Highest systematic: modelling radiation HF jets ggF: 25% on μ_{HH}

-Data-taking: correlated (apart resolved bbbb, different calibration version)
-physics objects: correlated
-theory: correlated
-systematics highly constrained or pulled: uncorrelated (but impact choice negligible)

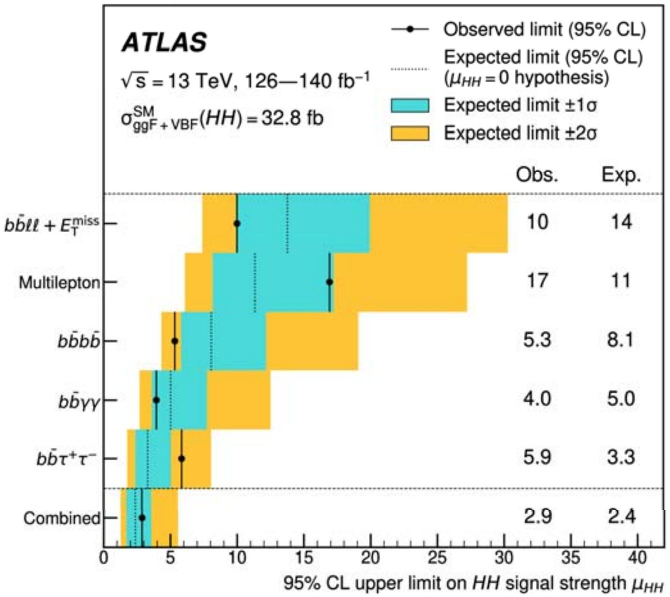
Non-resonant HH Combination

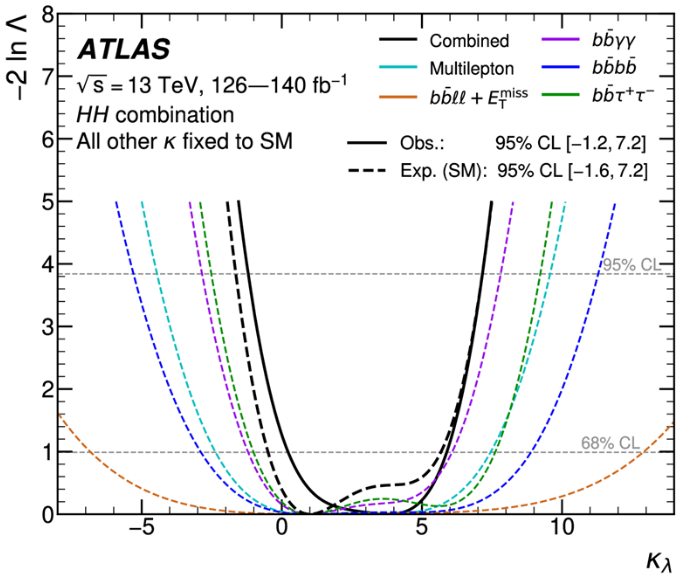
- Channels (overlap data & MC: <1% in SR⇔negligible) $f(\kappa_\lambda)$ of 1-H neglected

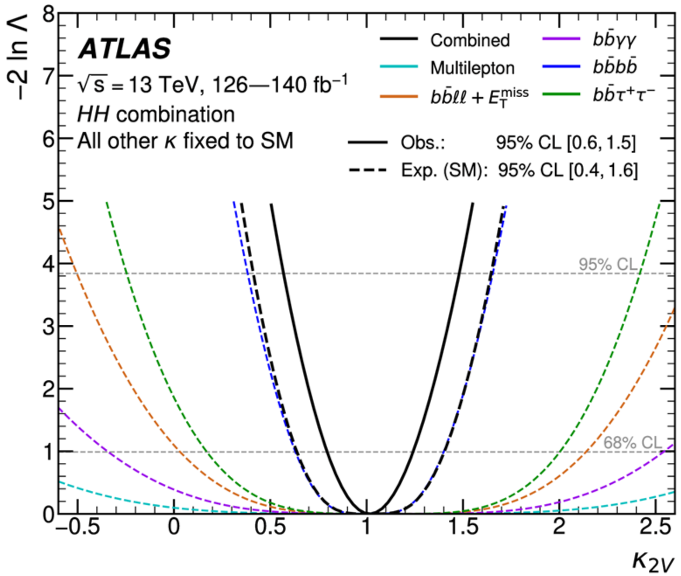
bbbb (resolved, boosted), bbττ (1 τ_{had}⊥ bbll+MET), bbγγ, multilepton (bbZZ*, VV*VV*, VV*ττ, ττττ, γγVV*, γγττ)
, bbll+MET (bb + (ZZ*, WW*, ττ)→ll)

- Final DV: m_{HH}, $m_{\gamma\gamma}$, MVA

- Limit on HH







bbττ most sensitive

bbγγ most sensitive

bbbb most sensitive: (boosted & deficit data)

expected: 17% improvement
13%: bbττ, bbγγ, bbbb
4%: add multilepton, bbll+MET

κ_λ, 95 % CL
obs :]-1.2 ; 7.2[
exp:]-1.6 ; 7.2[

κ_{2V}, 95 % CL
obs :]0.6 ; 1.5[
exp :]0.4 ; 1.6[

Best expected sensitivy to date on μ_{HH} & κ_λ

Non-resonant HH Combination

HEFT constraints

using 3 most sensitive channels: bb$\tau\tau$, bb$\gamma\gamma$, bbbb

(VBF boosted ignored: only sensitive to c_{hhh}, prediction not available for this process)

- 95% CL intervals

obs: $-0.38 < c_{gghh} < 0.49$ (exp: $-0.36 < c_{gghh} < 0.36$)

$-0.19 < c_{tthh} < 0.70$ (exp: $-0.27 < c_{tthh} < 0.66$)

Most stringent constraints to date

HH→bb+ll+MET

ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, JHEP 02 (2024) 037

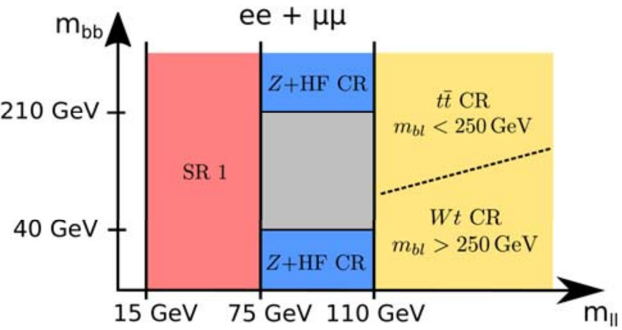
- Target

bb+WW*/ZZ*/ττ→bb+ll+ν

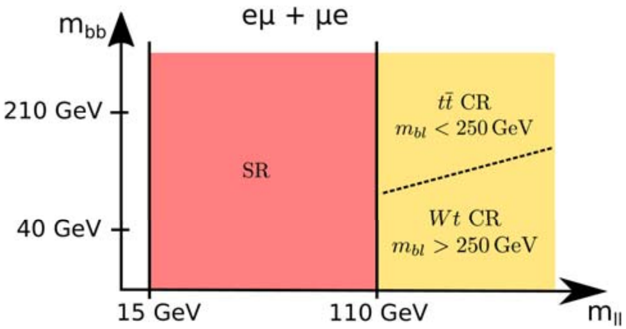
- Selection

=2 b-jet
=2 OS leptons (e or μ)
No requirement on MET (ensure high stat for MVA)
Veto event bad jet (suppr. misid jets)
SR and CR: f(m_{ll})

same flavour



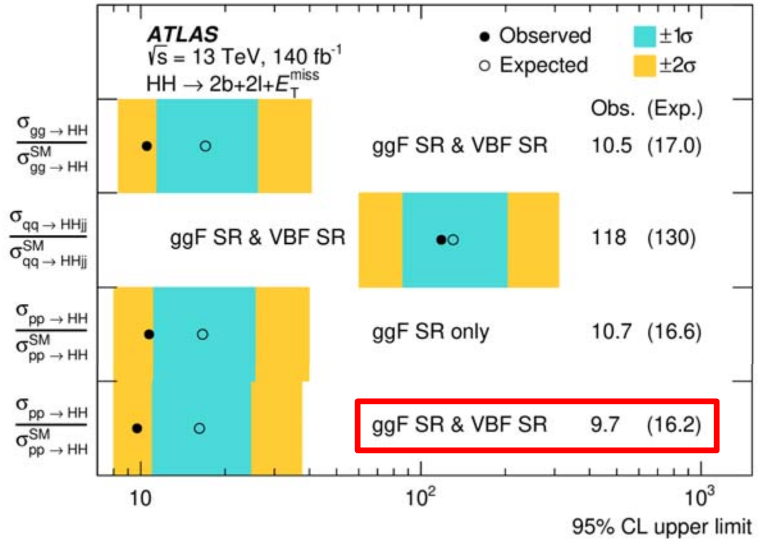
≠flavour



gray: negligible

Categories ggF/VBF
Final discriminant: MVA
Train BDT VBF on κ_λ=0

Oct. 2023



- κ_λ 95 % CL

obs : [-6.2 ; 13.3]
exp: [-8.1 ; 15.5]

- κ_{2V} 95 % CL

obs : [-0.17 ; 2.4]
exp: [-0.51 ; 2.7]

Significant improvement wrt previous publication

Non resonant VBF HH(bbbb) boosted

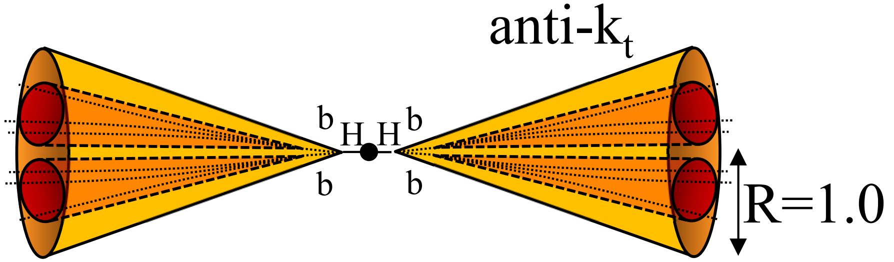
ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=140 fb^{-1},
PLB 858 (2024), 139007

- Selection

-2 b-tagging: DNN
(↑ 50% sensitivy wrt old track-jet b-tagging)
[but not GNN]

WP: 60% eff (rej multijets: 92, rej tt: 31)

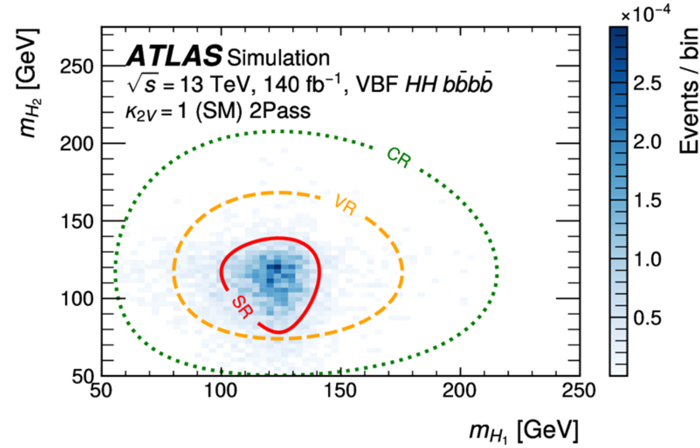
-VBF jets: 2 small-R jets, $|\Delta\eta(j, j)|>3$, $m_{jj}>1$ TeV



Signal Region, Validation Region (syst.), Control Region

$$\sqrt{\left(\frac{m_{H_1} - 124\ GeV}{f(m_{H_1})}\right)^2 + \left(\frac{m_{H_2} - 117\ GeV}{f(m_{H_2})}\right)^2} < thr$$

Detector effects, E lost ν from b-hadrons, out-of-cone radiation



SR to max. Z for κ_{2V}=0 (proxy BSM)⇔maximise sensitivity κ_{2V}

Remove events passing resolved (suppr. overlap)

Efficiency: non-resonant: 1% (BSM)→0.02% (SM), resonant: 5-10%=f(m_X, Γ_X)

- Background

Primary: multijets (10% tt), data-driven : CR 1 b-J

Negligible: 1-H, dibosons

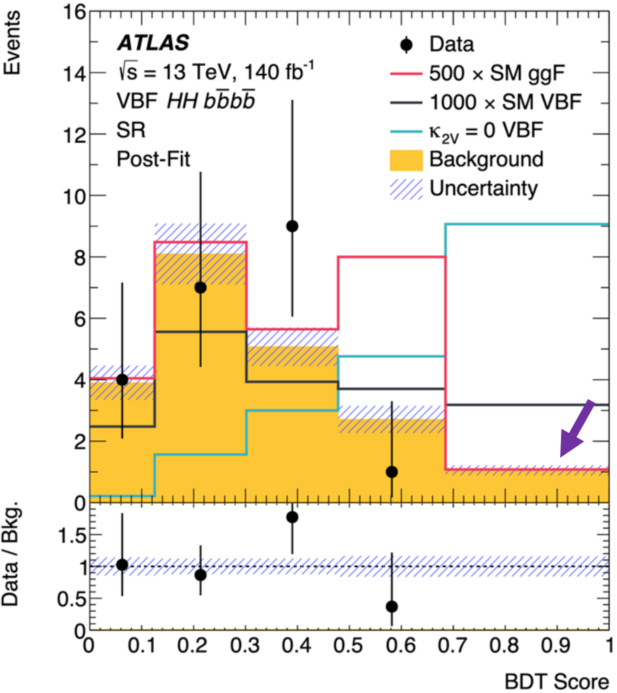
- Final Discriminant variables: BDT (XGBoost)

Training: non-resonant: κ_{2V}=0 VBF HH (proxy BSM),
resonant: mass-parametrised BDT (pBDT)

Non resonant VBF HH(bbbb) boosted

- ggHH considered bkg for probing κ_{2V}

(+contour (κ_λ, κ_{2V}): ggHH considered signal)



deficit data in most signal-like bin

- κ_{2V} interval at 95% CL (κ_λ=1)

obs: [0.52 ; 1.52]

exp: [0.32 ; 1.71]

κ_{2V}=0 excluded w/ Z_{obs}=3.4

Z_{exp}=2.9

Combine w/ resolved

obs: [0.55 ; 1.49]

exp: [0.37 ; 1.67]

-obs stronger than exp

-allowed range /2 wrt previous ATLAS publication

κ_{2V}=0 excluded w/ Z_{obs}=3.8

Z_{exp}=3.3

- expected contribution boosted for κ_λ : marginal wrt resolved
- Complementary analyses for sensitivity:

κ_λ (driven resolved) & κ_{2V} (driven boosted)

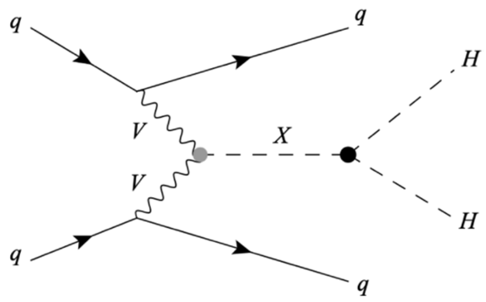
[ggHH considered signal for probing κ_λ]

VBF HH(bbbb) boosted

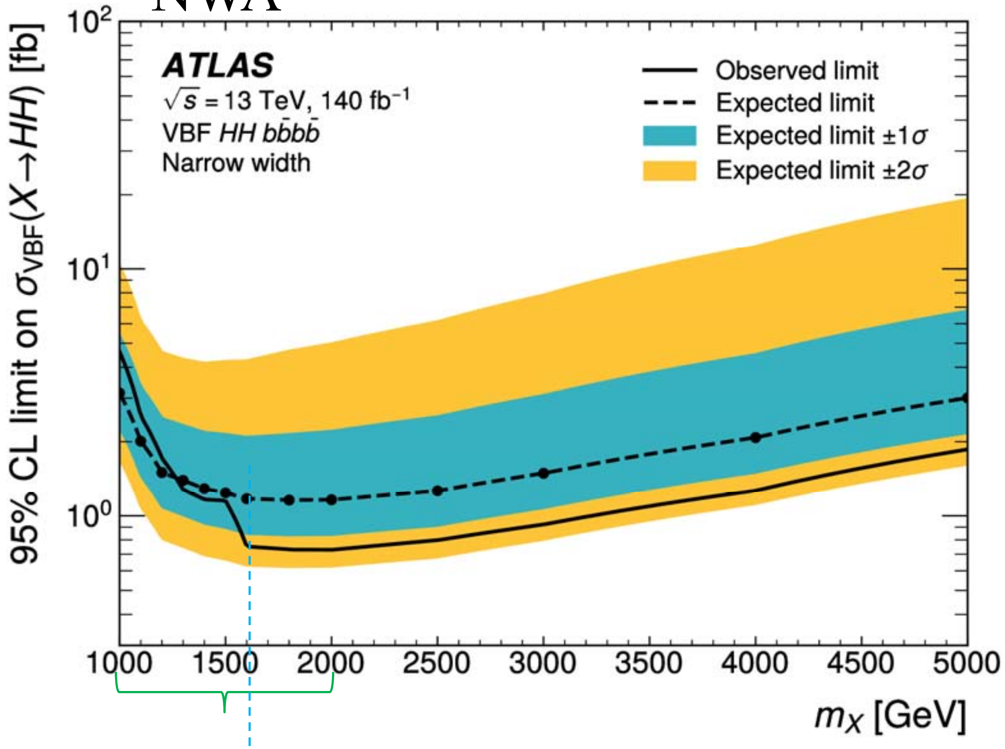
ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, PLB 858 (2024), 139007

- Resonant, X, spin 0

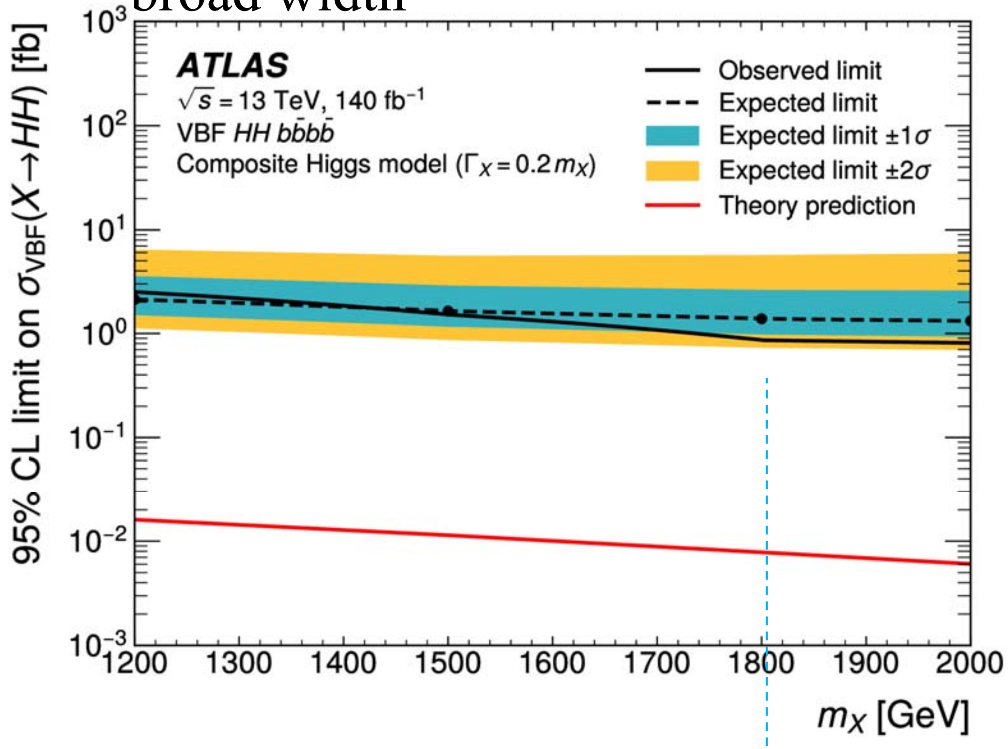
Mass-parametrised BDT (pBDT)



NWA



broad width



Loss efficiency in 2 b-tagging in highly boosted regime

No data in signal-like bin BDT

Non-resonant HH (bbττ)

ATLAS, Run 2 Legacy, √s=13 TeV, L=140 fb^{-1}, PRD 110 (2024) 032012

- 3 SR: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ (e, μ): Single-Lepton Trigger or Lepton-plus-T_{had} Trigger April 2024

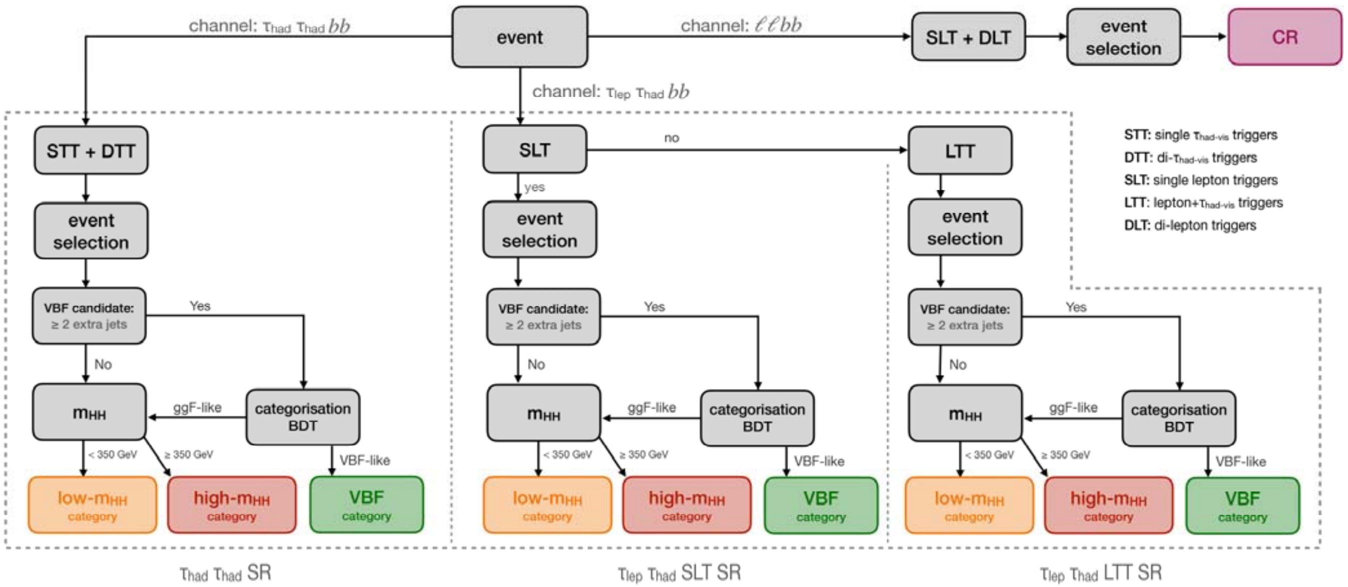
  ($\tau_{lep}\tau_{lep}$: different analysis)

  Id(τ_{had}): Recurrent Neural Network

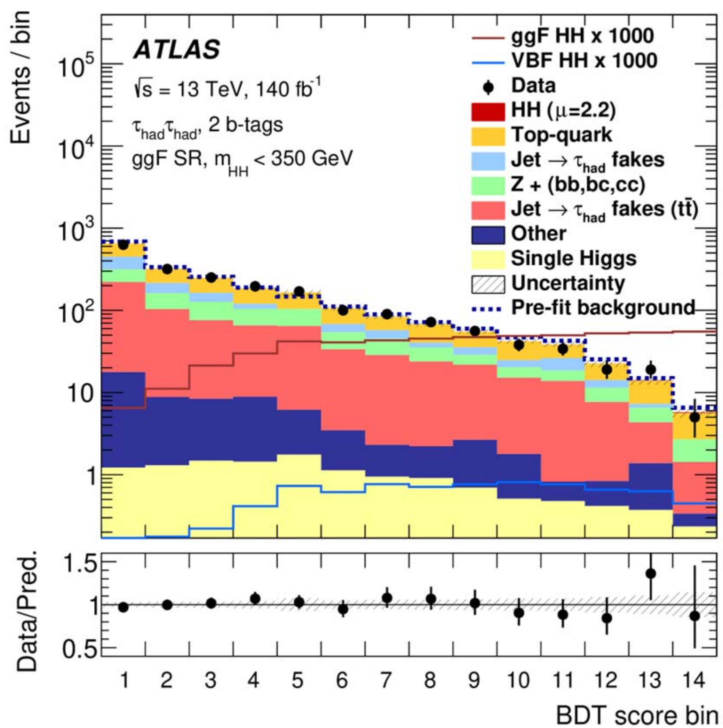
2 b-jets (DL1r, 77% WP), $m^{\tau\tau}_{MMC}$>60 GeV, + selection for each SR

Acceptance: 4%

split in 3 categories (w/ category BDT): SR: low (BSM)/high mass (SM),VBF + CR



- Binned likelihood fit: BDT



- Background: data-driven, simulation, combination

Non-resonant HH ($bb\tau\tau$)

- 95% limits on μ_{HH} (driven by $\tau_{had}\tau_{had}$):
obs: 5.9xSM
exp: 3.3xSM
Asymptotic agree within 7% w/ toys
(improved* by 15%)

- κ_λ 95% CI:
obs:]-3.1 ; 9.0[
exp:]-2.5 ; 9.3[
(improved* by 11%)

- κ_{2V} 95% CI:
obs:]-0.5 ; 2.7[
exp:]-0.2 ; 2.4[
(improved* by 19%)

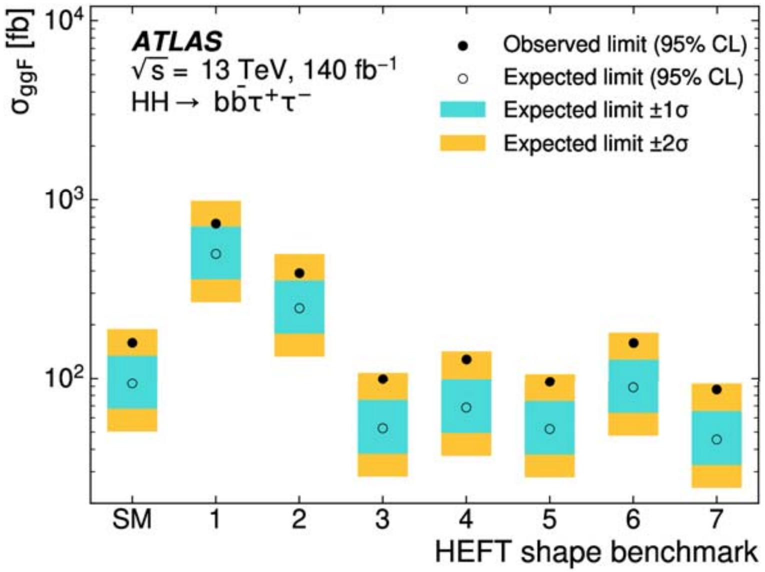
(*Improved classification + VBF HH category)

EFT interpretation

- HEFT
7 m_{hh} benchmark scenarios
(from arXiv:2304.01968 [hep-ph])

direct limits:
c_{gghh}, c_{tthh}

- SMEFT: c_H, $c_{H\Box}$



Wilson coefficient	Observed 95% CI	Expected 95% CI
c_{gghh}	[−0.51, 0.58]	[−0.42, 0.44]
c_{tthh}	[−0.40, 0.84]	[−0.32, 0.72]
c_H	[−19.4, 10.0]	[−19.1, 8.6]
$c_{H\Box}$	[−12.6, 11.6]	[−8.5, 11.1]

ATLAS	SM	operator
c_H	0	$(\phi^\dagger\phi)^3$
$c_{H\Box}$	0	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$

HH multileptons

ATLAS, Run 2, √s=13 TeV, L=140 fb^{-1}, JHEP 08 (2024) 164

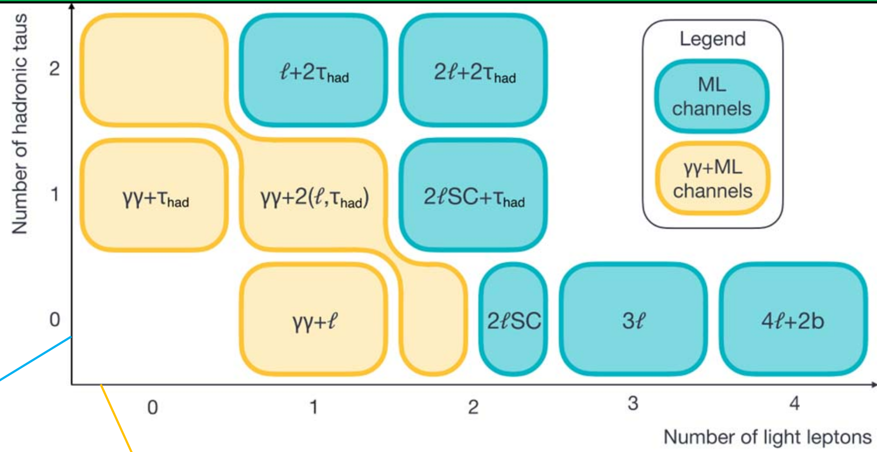
May 2024

- Final state w/ multi leptons & τ_{had}

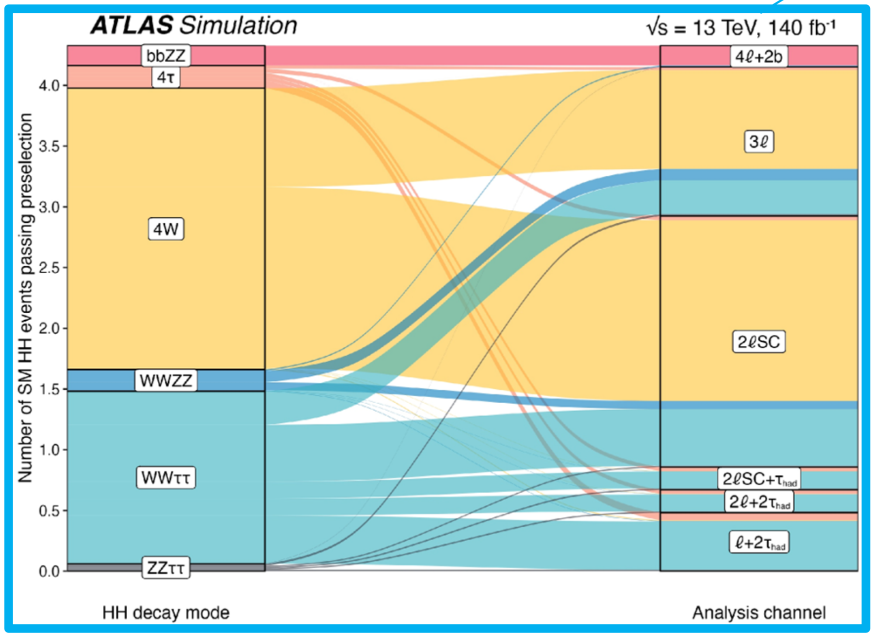
Subchannels: #objects

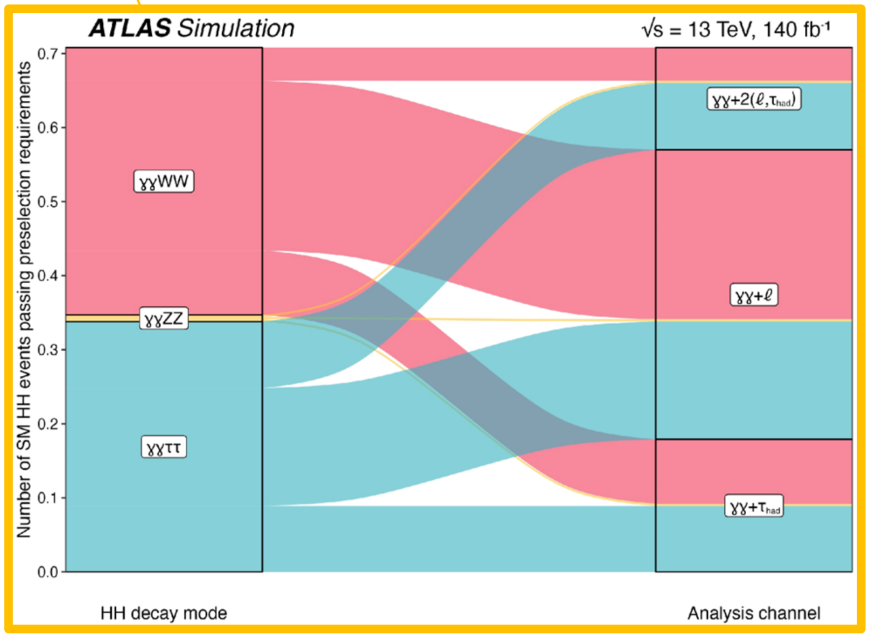
Selection ⊥ other analyses

Dominant bkg: dibosons



- Contributions





Final DV: γγ+ML: $m_{\gamma\gamma}$, others: BDT

Signal: ggF HH, VBF HH

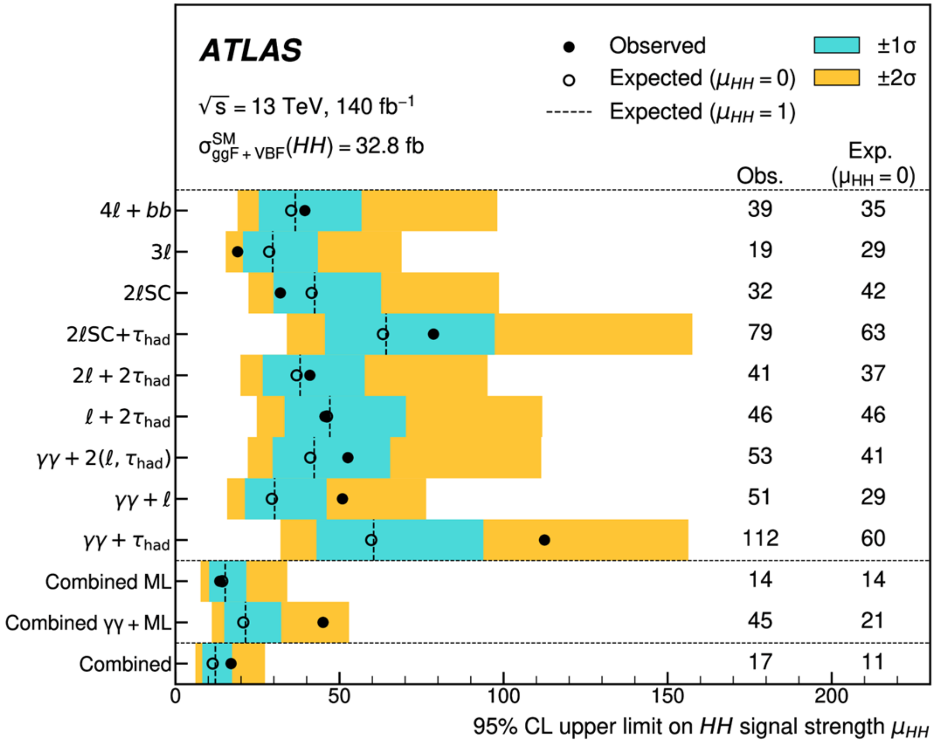
Background: normalisation w/ CR

HH multileptons

- Limit at 95% CL

obs: 17xSM

exp: 11xSM

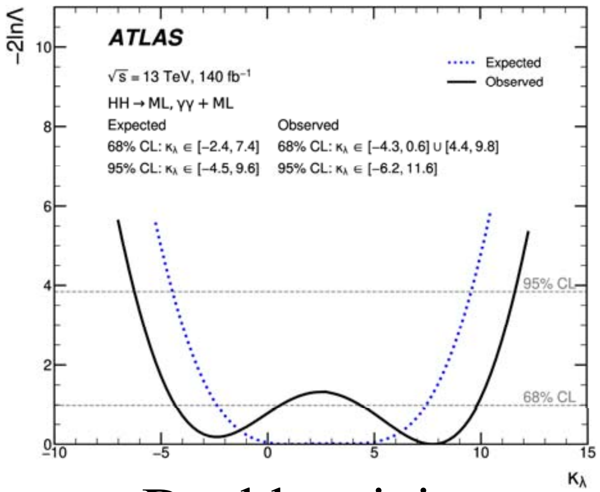


Asymptotic results within 8% w/ toys

- κ_λ, 95 % CL

obs :]-6.2 ; 11.6[

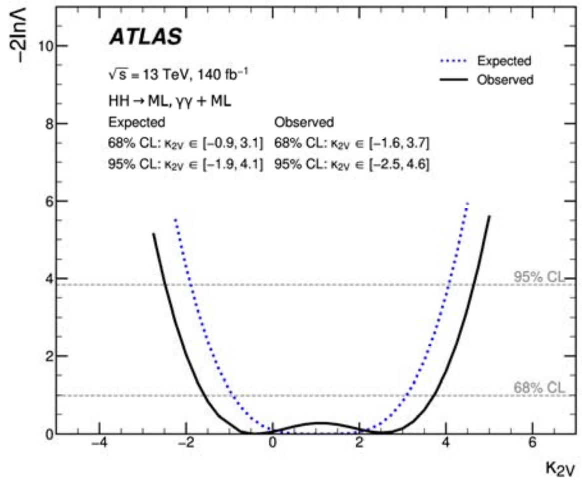
exp:]-4.5 ; 9.6[



- κ_{2V}, 95 % CL

obs :]-2.5 ; 4.6[

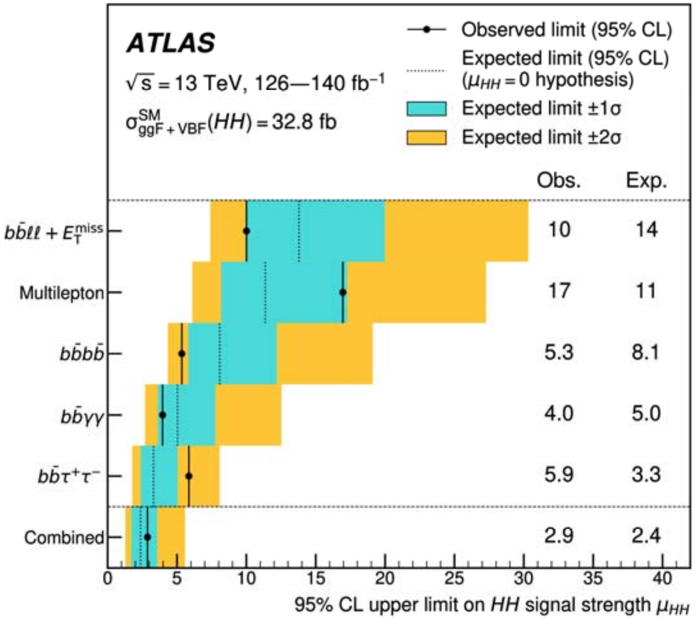
exp:]-1.9 ; 4.1[



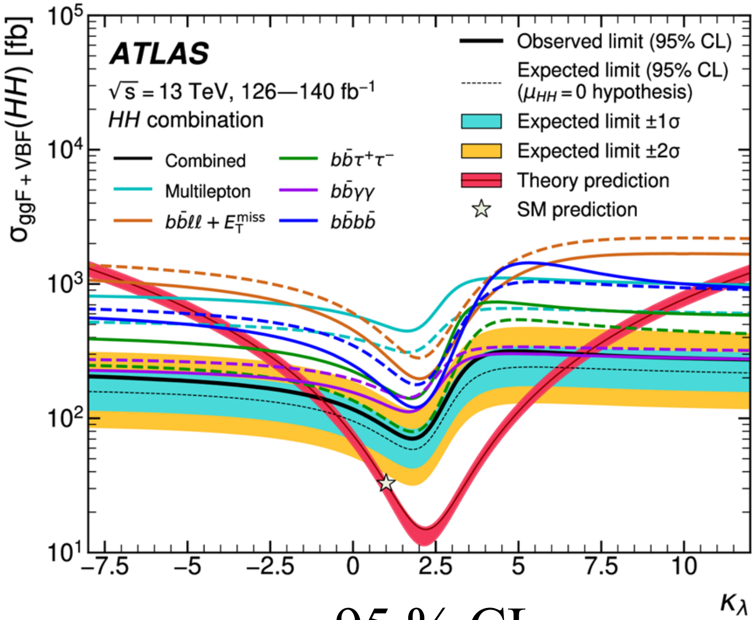
Double minimum structure: degeneracy competing $\sigma=f(\kappa_\lambda)$, eff=$f(\kappa_\lambda)$

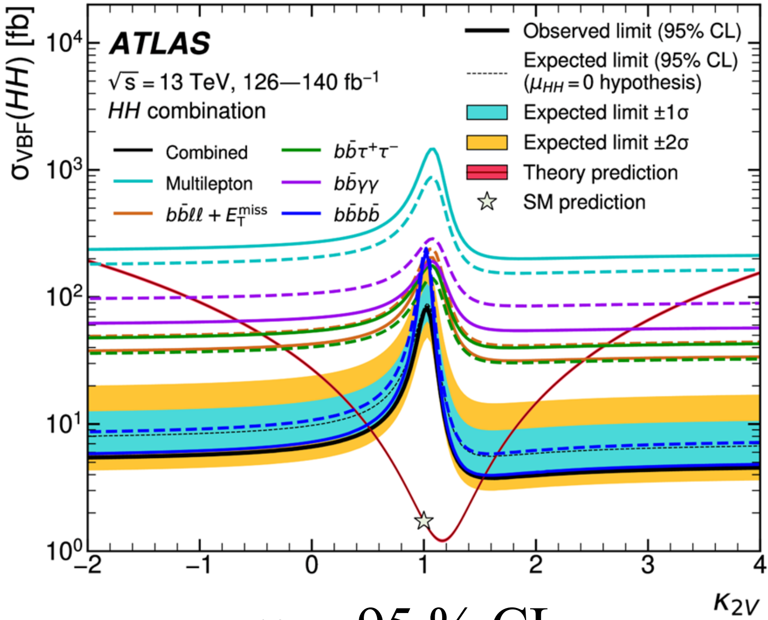
Non-resonant HH Combination

- Limit on HH



f(κ_λ) of 1-H neglected





expected: 17% improvement
13%: bbττ, bbγγ, bbbb
4%: add multilepton, bbll+MET

κ_λ, 95 % CL
obs :]-1.2 ; 7.2[
exp:]-1.6 ; 7.2[

κ_{2V}, 95 % CL
obs :]0.6 ; 1.5[
exp :]0.4 ; 1.6[

Best expected sensitivy to date on μ_{HH} & κ_λ

bbbb most sensitive
(thx boosted)
+deficit data

Non-resonant HH Combination

HEFT constraints

Uses 3 most sensitive channels: bbττ, bbγγ, bbbb

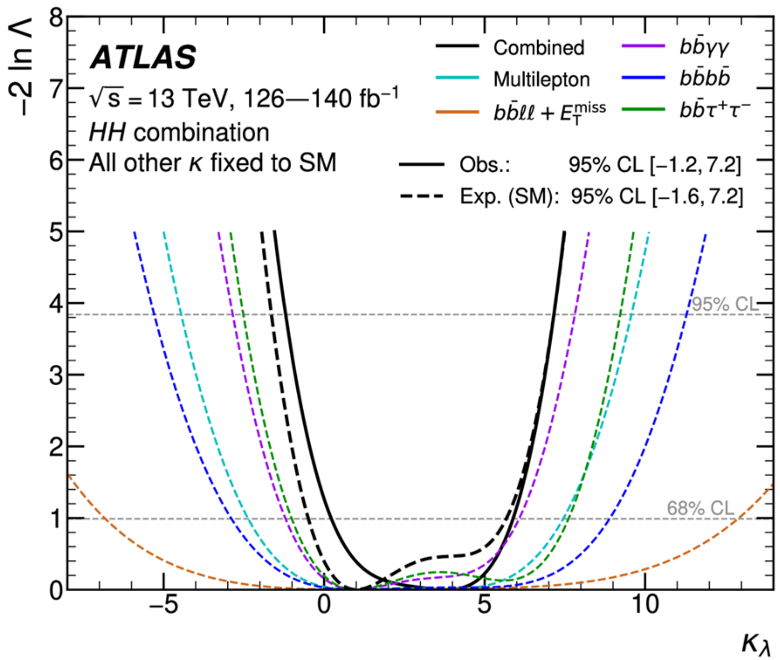
VBF HH ignored (only sensitive to c_{hhh}), prediction not available for this process

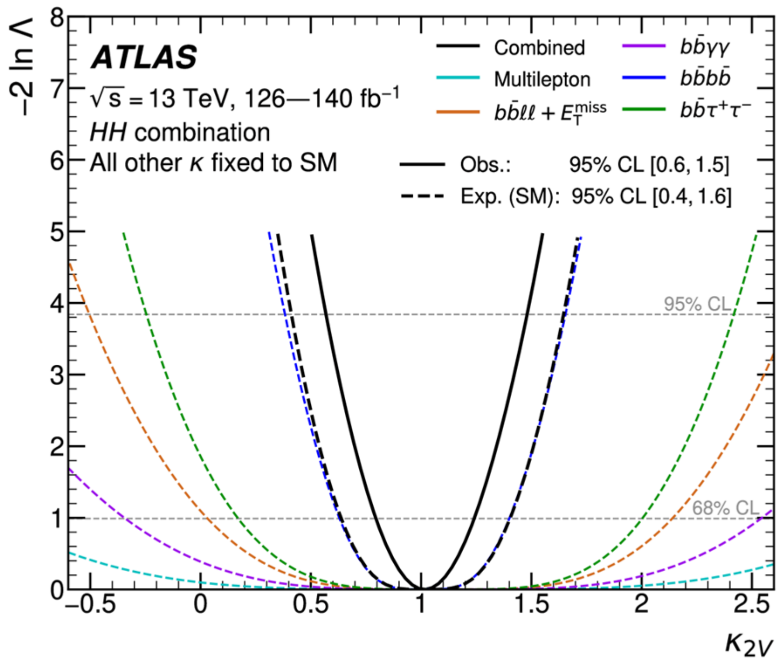
- 95% CL intervals

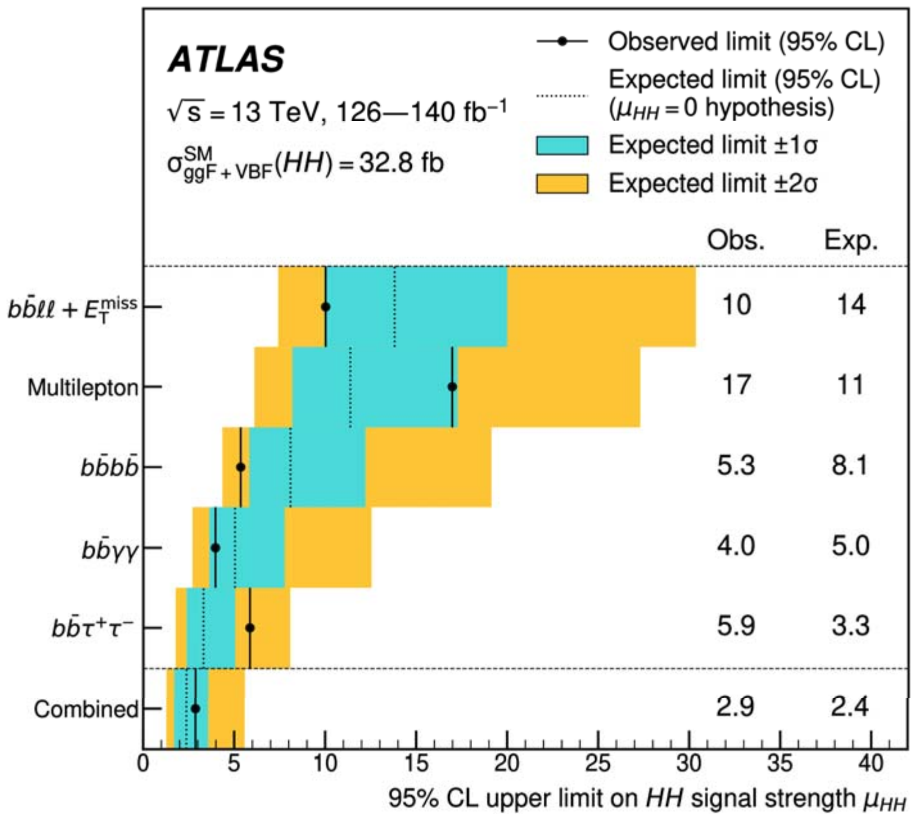
obs: $-0.38 < c_{gghh} < 0.49$ (exp: $-0.36 < c_{gghh} < 0.36$)

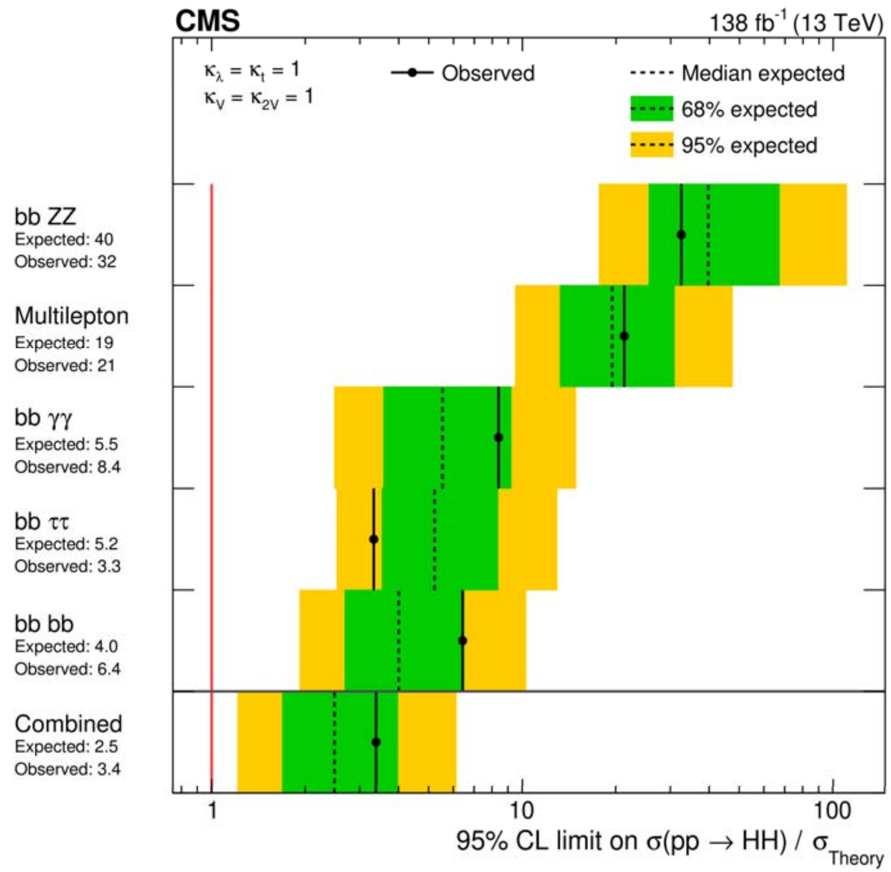
$-0.19 < c_{tthh} < 0.70$ (exp: $-0.27 < c_{tthh} < 0.66$)

Most stringent constraints to date



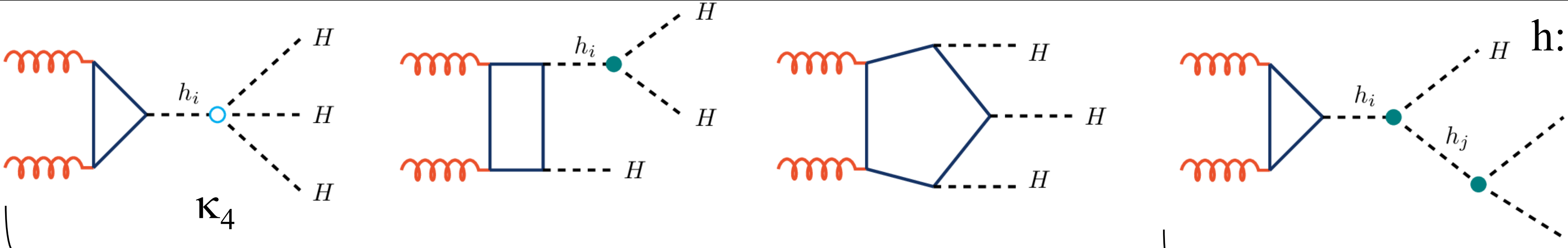



ATLAS
√s = 13 TeV, 126—140 fb⁻¹
σ^SM_ggF+VBF(HH) = 32.8 fb
Observed limit (95% CL)
Expected limit (95% CL) (μHH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Obs.
Exp.
bb̄ℓℓ + E_T^miss
10
14
Multilepton
17
11
bb̄bb̄
5.3
8.1
bb̄γγ
4.0
5.0
bb̄τ⁺τ⁻
5.9
3.3
Combined
2.9
2.4
95% CL upper limit on HH signal strength μHH


CMS
138 fb⁻¹ (13 TeV)
κλ = κt = 1
κV = κ2V = 1
Observed
Median expected
68% expected
95% expected
bb ZZ
Expected: 40
Observed: 32
Multilepton
Expected: 19
Observed: 21
bb γγ
Expected: 5.5
Observed: 8.4
bb ττ
Expected: 5.2
Observed: 3.3
bb bb
Expected: 4.0
Observed: 6.4
Combined
Expected: 2.5
Observed: 3.4
95% CL limit on σ(pp → HH) / σTheory

HHH bb bb bb

ATLAS, Run 2, √s=13 TeV, L=126 fb[-1], CERN-EP-2024-285



h: H, X, S

non-resonant

Resonant:
cascade X→SH

- Scenarios:

-SM non resonant

-Resonant, H+2 real scalar: X ($325<m_X<575$ GeV), S (200<mS<350 GeV)

$m_X>m_S$ Two Real Scalar Model (TRSM)

-Heavy Resonant: heavy spin-0 X, S, $550<m_X<1500$ GeV, $275<m_S<1000$ GeV

$m_X>m_S$, narrow or wide

Categories: SR: 6b, CR: 4b, 5b

HHH bb bb bb

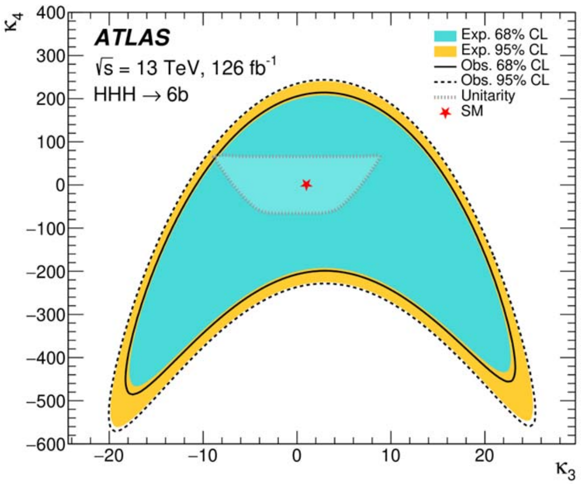
ATLAS, Run 2, √s=13 TeV, L=126 fb[-1], CERN-EP-2024-285

- Pairing: over all pairs, minimize $|m_{H1}$-120 GeV$|+|m_{H2}$-115 GeV$|+|m_{H3}$-110 GeV$|$
  values: detector effects, energy lost from neutrinos, out-of-cone radiation
  efficiency: SM: 61%, BSM: 74-84%

Bkg: dominated by QCD multijets: data-driven: extrapolate from CR
Profile likelihood, DNN

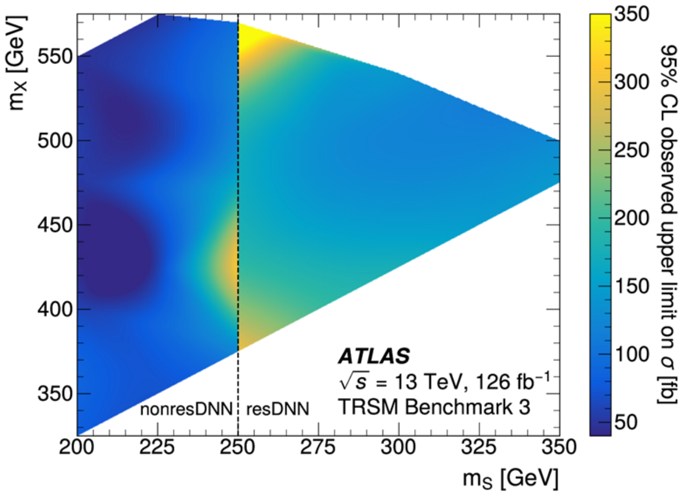
- Non-resonant

Limit μ_{HHH}=750xSM

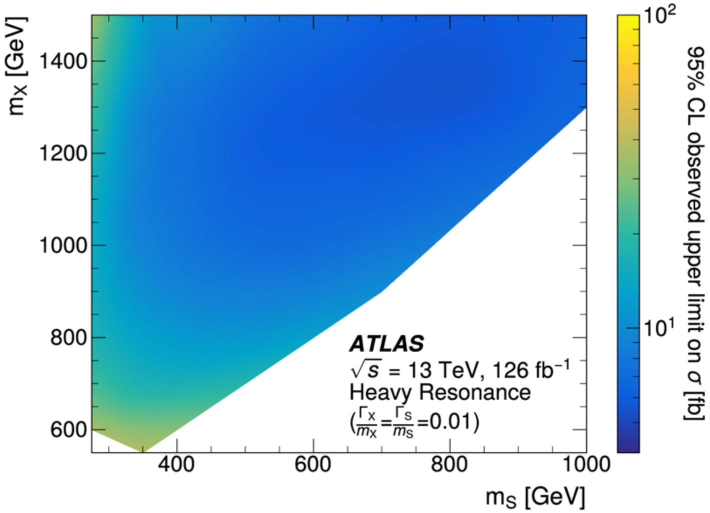


For κ_4=1, -11<κ_λ<17 at 95% CL

- Resonant



- Heavy Resonant, NWA



(+wide)

ATLAS Combination HH resonant

ATLAS, Run 2, √s=13 TeV, L=126-139 fb^{-1}, PRL 132 (2024) 231801

- Narrow width (10 MeV) gg→X, J=0 resonance

-negligible wrt experimental resolution

-neglect interference non-resonant hh (Γ_H low)

Systematics: data-taking: correlated

Reco: correlated where appropriate

b-tagging: DL1r, eff: 77%, rej j: 170, rej c: 5

-bbbb: resolved (R=0.4), BDT to pair b-jets
boosted (R=1.0)

m_{HH}: final DV, kin. rescaling m_{bb}=125

Resolution: ≈5-6%

-bbττ: Higgs decays: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$,

Final DV: mass-parameterised NN

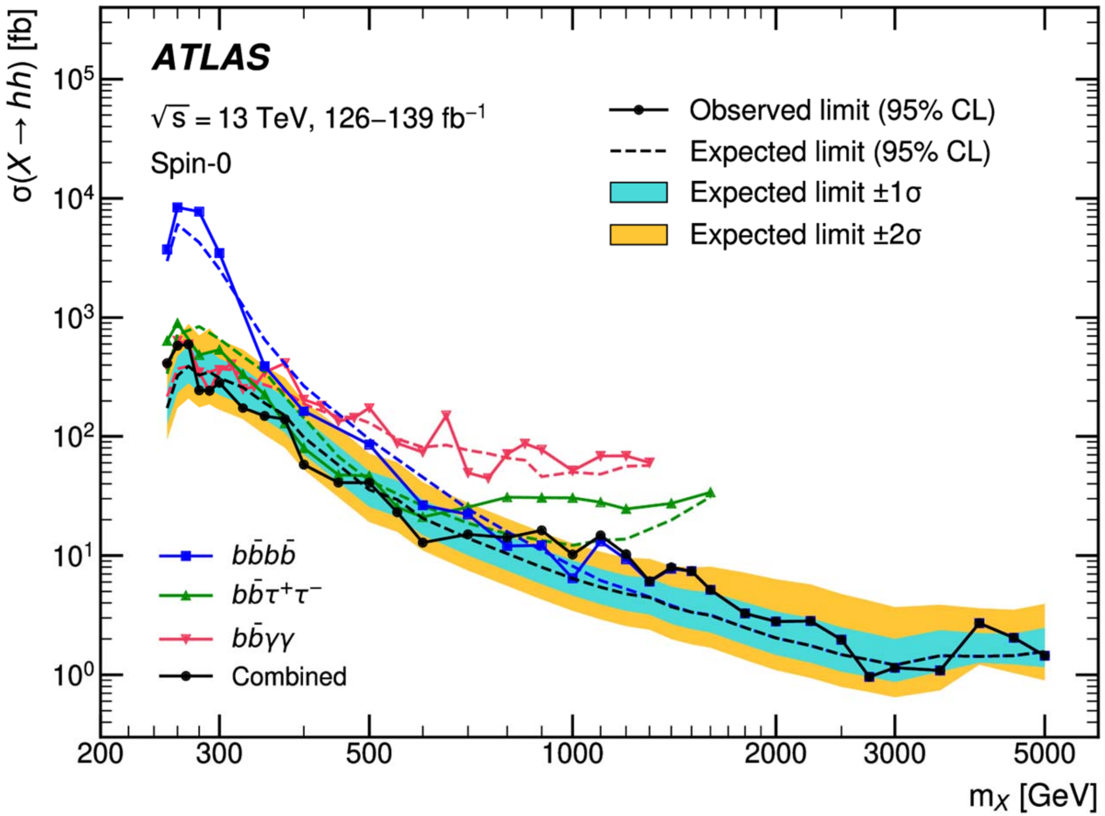
m_X resolution: 5-10%

-bbγγ: 2 BDT combined

1 BDT signal vs ttγγ ; 1 BDT signal vs 1-H

Final DV: $m_{\gamma\gamma}$ (resolution 1%)

Resolution m_{hh}: ≈2-3%



best bbγγ best bbττ best bbbb

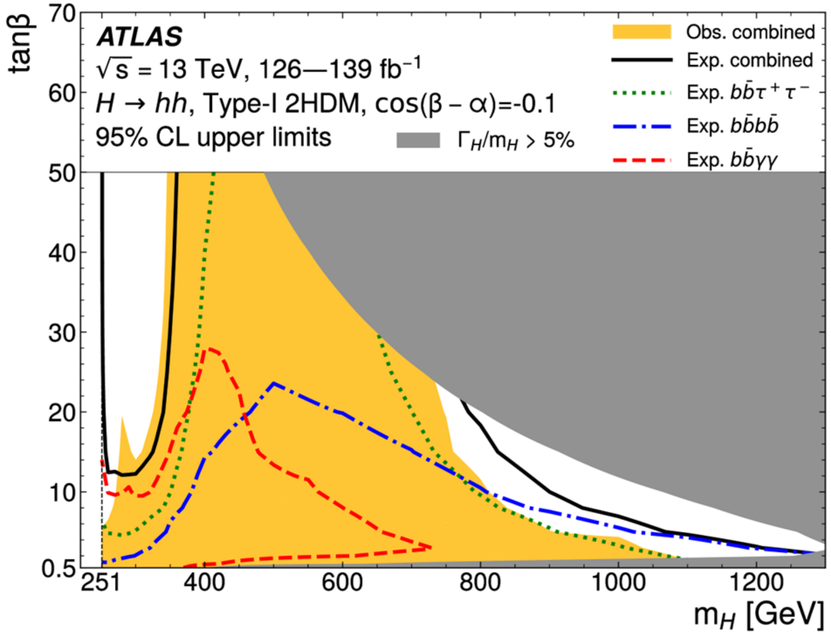
ATLAS Combination HH resonant

Limit: interpretations

Neglect interference=approximation

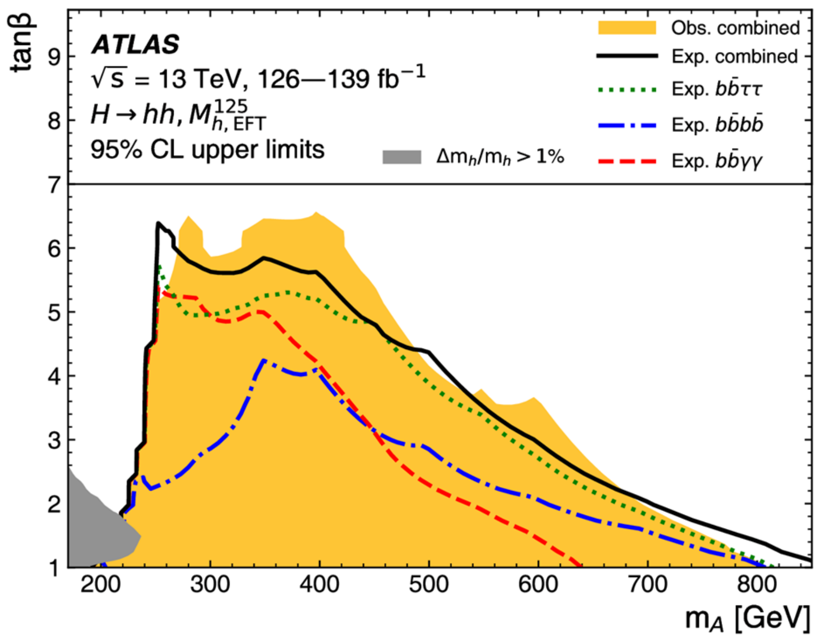
2HDM Type I

+other planes



MSSM

+other benchmarks

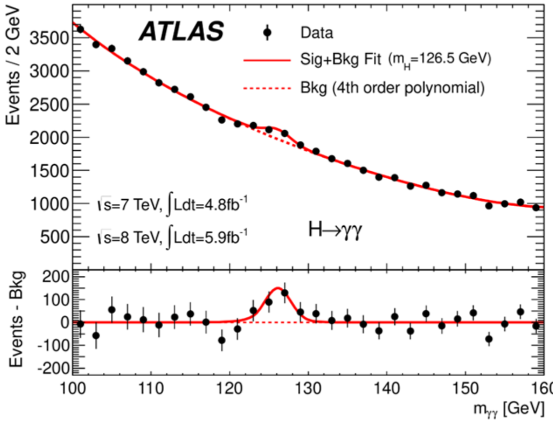


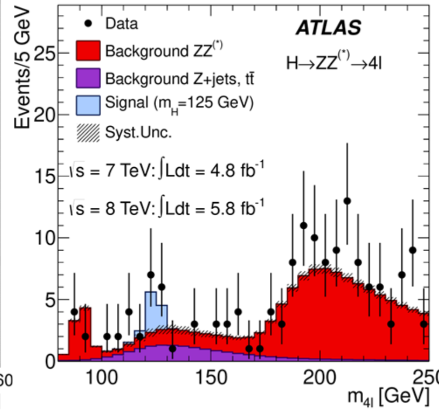
Constrain parameter space not previously excluded

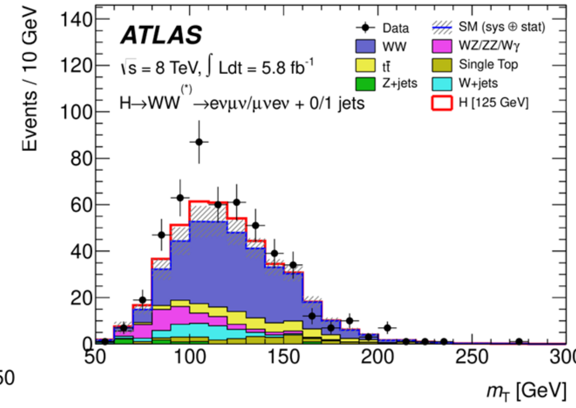
Conclusions

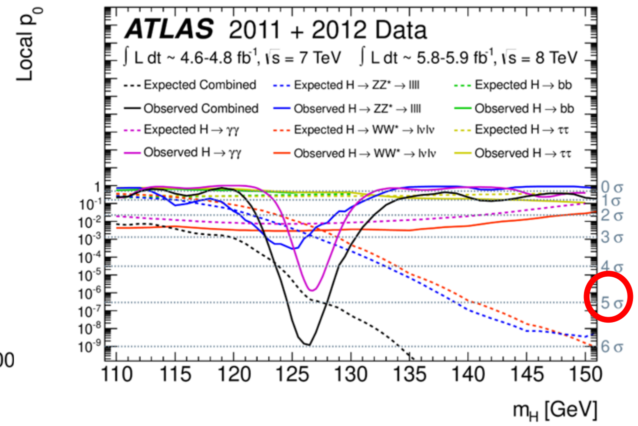
Review Run 2, Phys. Rep 11 (2024) 001

Run 1 (2011+2012): Higgs discovery









→couplings to bosons

Followed by first measurements of properties

-Mass: m_H=125.09 ± 0.24 GeV

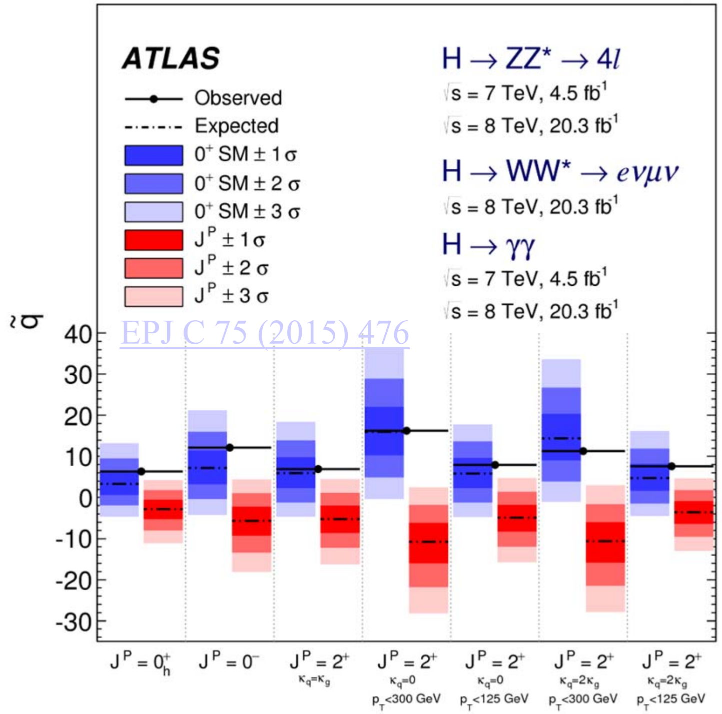
used as input for almost all measurements of Run 2

-Differential cross-sections

-Spin: boson: …→2 bosons

…→2 photons: exclude spin 1

-CP alternatives excluded

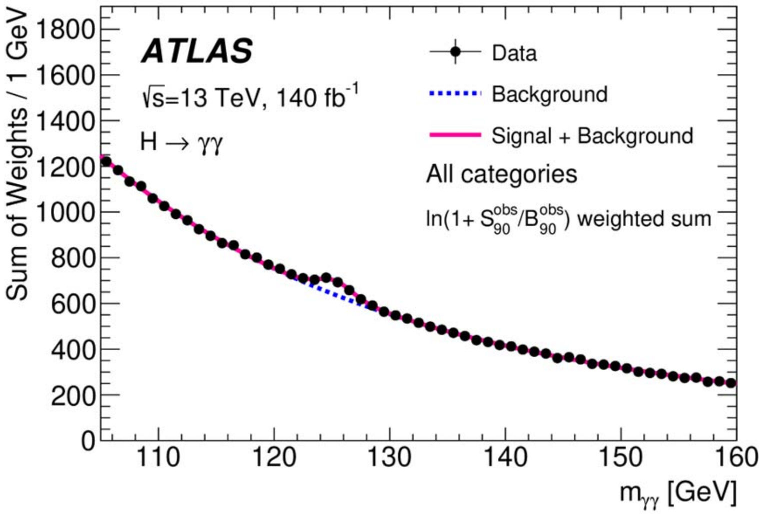


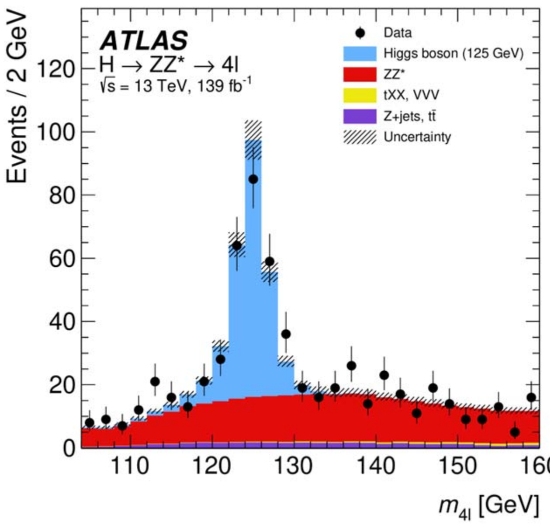
Conclusions

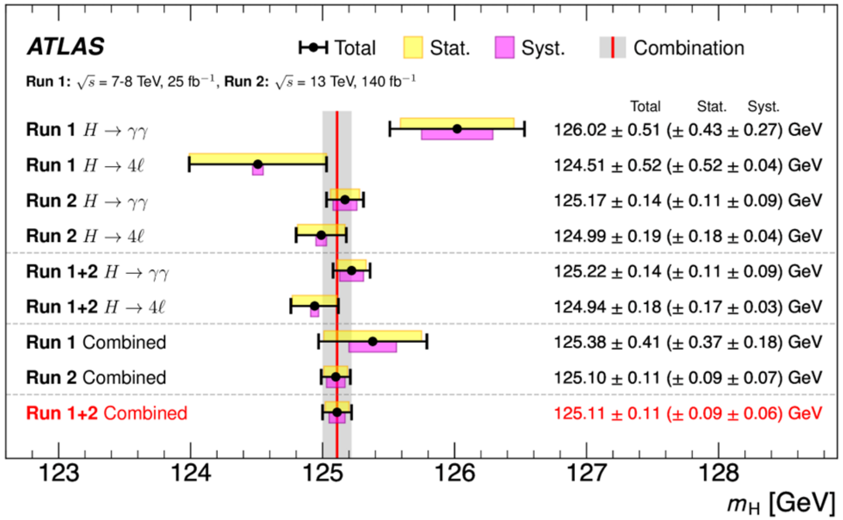
Review Run 2, Phys. Rep 11 (2024) 001

After Run 1 Higgs discovery, couplings to bosons, and first measurements properties
Vast program of measurements with Run 2

- Mass & width







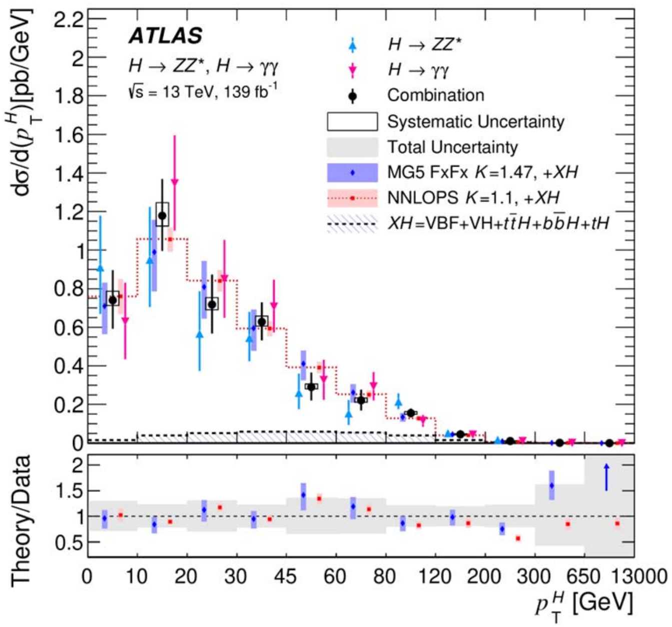
Better than per mill precision

- Higgs width Γ_H

(off-shell, on-shell): best sensitivity

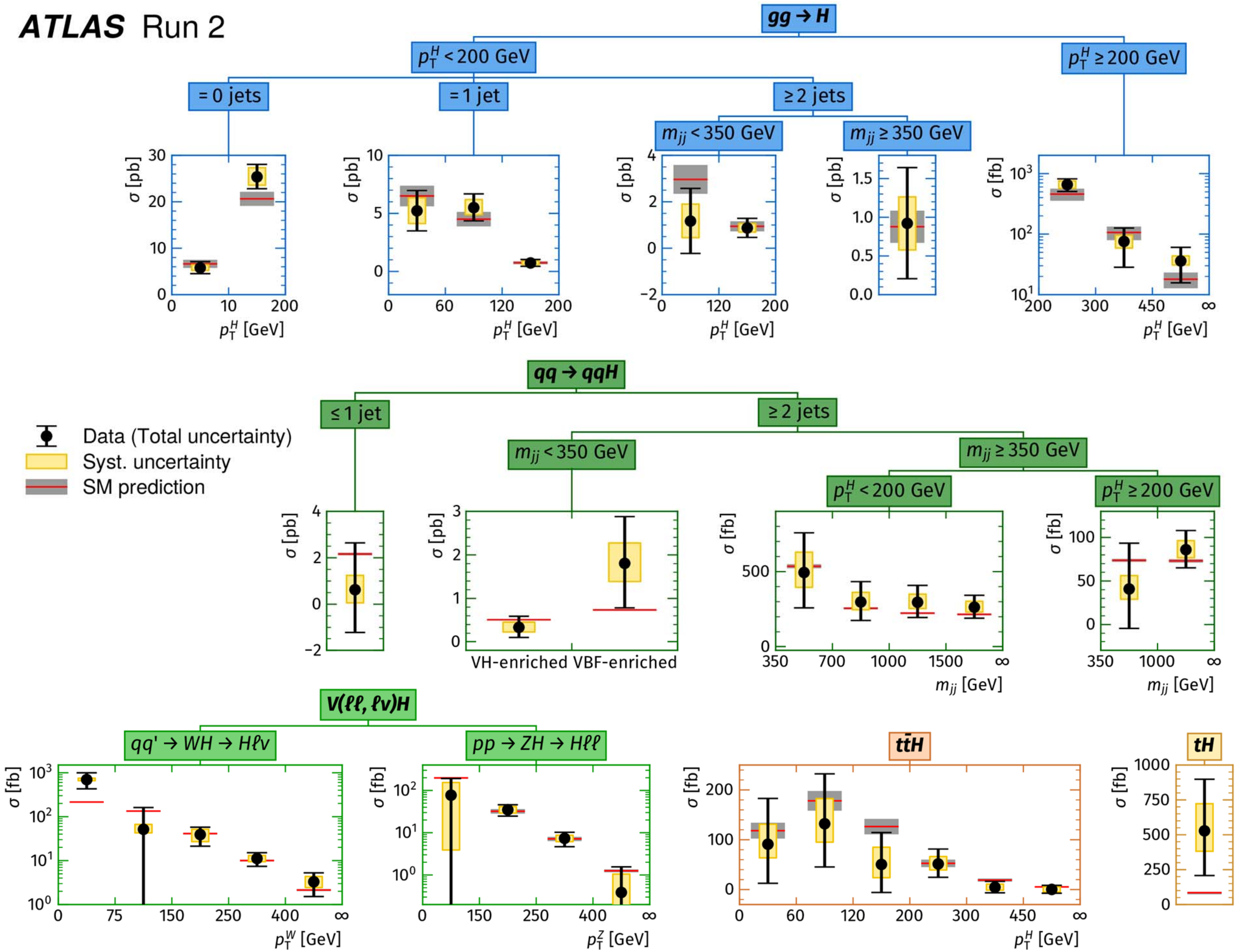
- Fiducial and dσ/dX

7, 8, 13, 13.6 TeV evolution
f(kinematics), eg: p_T^H, y_H, etc.



Conclusions

Production cross-section in various kinematic regions (STXS) & EFT interpretation



+EFT interpretation (already shown)

Conclusions

- Coupling to fermions

3nd generation

$H \rightarrow \tau\tau$, Z_{obs}=5.5, JHEP 08 (2016) 045

ttH, Z_{obs}=6.3 (Z_{exp}=5.1), PLB 784 (2018) 173

$H \rightarrow bb$, Z_{obs}=5.4 (Z_{exp}=5.5), PLB 786 (2018) 59

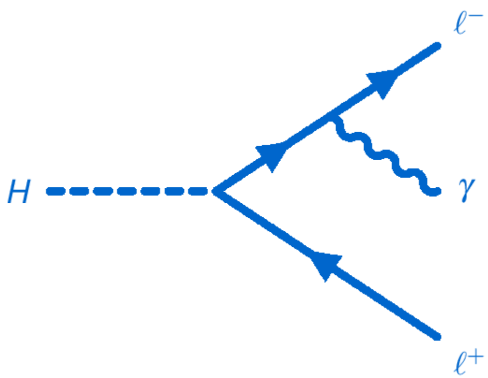
2nd generation

$H \rightarrow cc$, VH, 95% CL limit: obs: 26xSM (exp: 31xSM), EPJC 82 (2022) 717

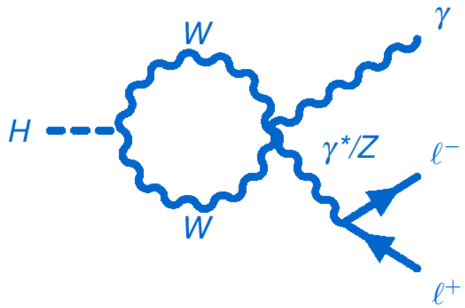
$H \rightarrow \mu\mu$, Z_{obs}=2.0 (Z_{exp}=1.7) PLB 812 (2021) 135980

- Rare loop-induced decays

$H \rightarrow ll\gamma$, Z_{obs}=3.2, (Z_{exp}=2.1), PLB 819 (2021) 136412



$H \rightarrow Z\gamma$, Zobs=2.2, (Z_{exp}=1.2), PLB 809 (2020) 135754



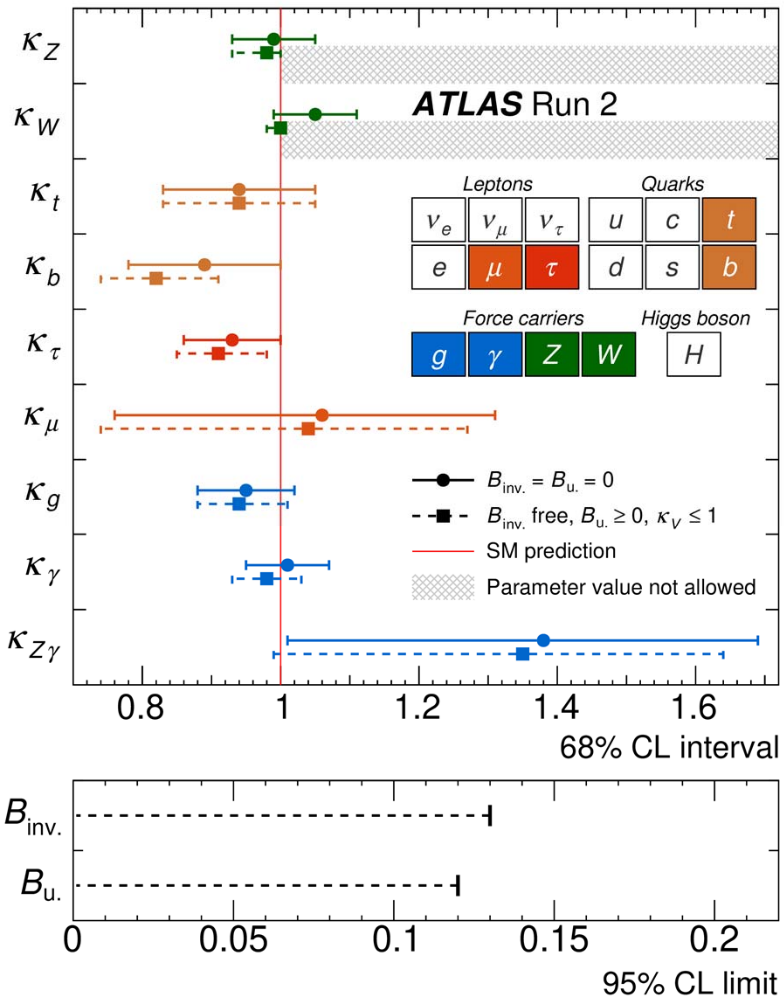
- More generally, establish most of phase space for Prod x Decay channels

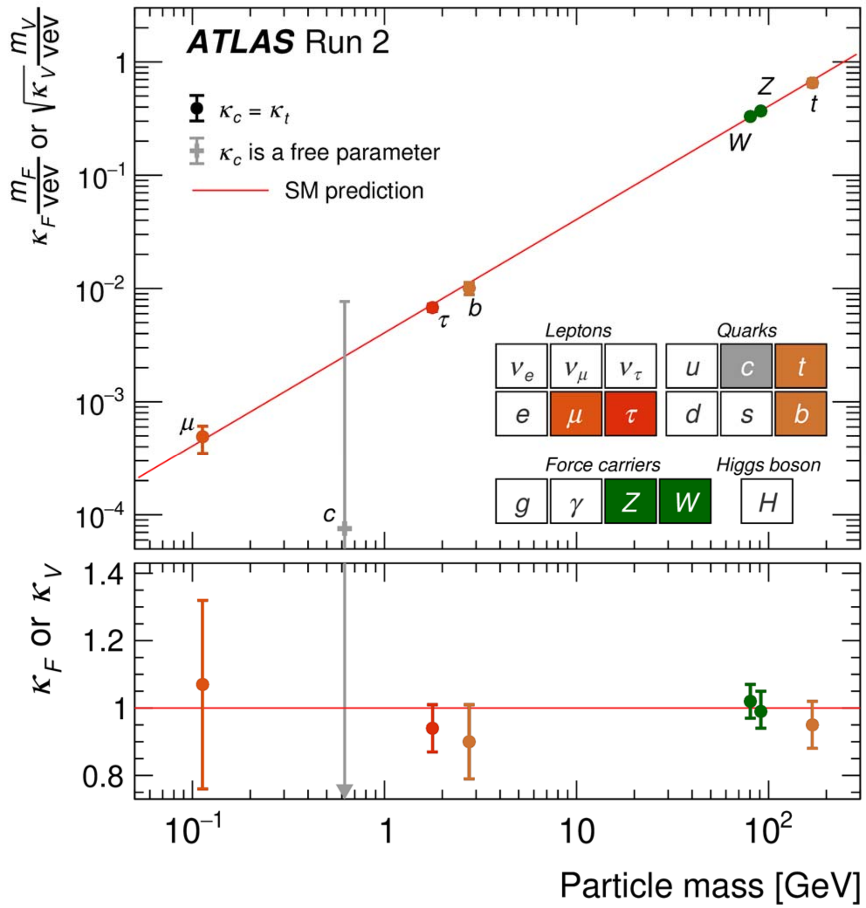
Conclusions

- Cross-sections & couplings from combination

μ=1.05 ± 0.06 (syst. dominated)

Couplings to other particles: κ-framework





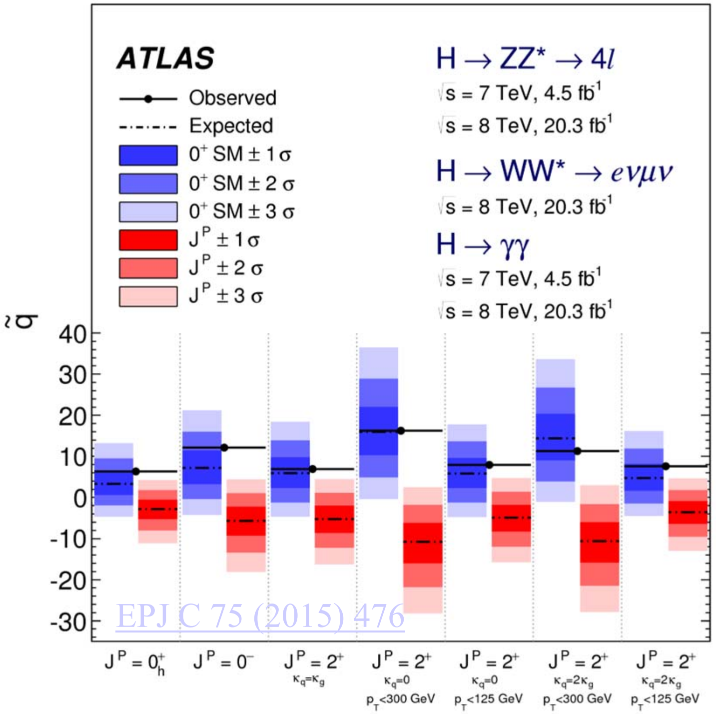
Production cross-section in various kinematic regions (STXS)

+EFT interpretation

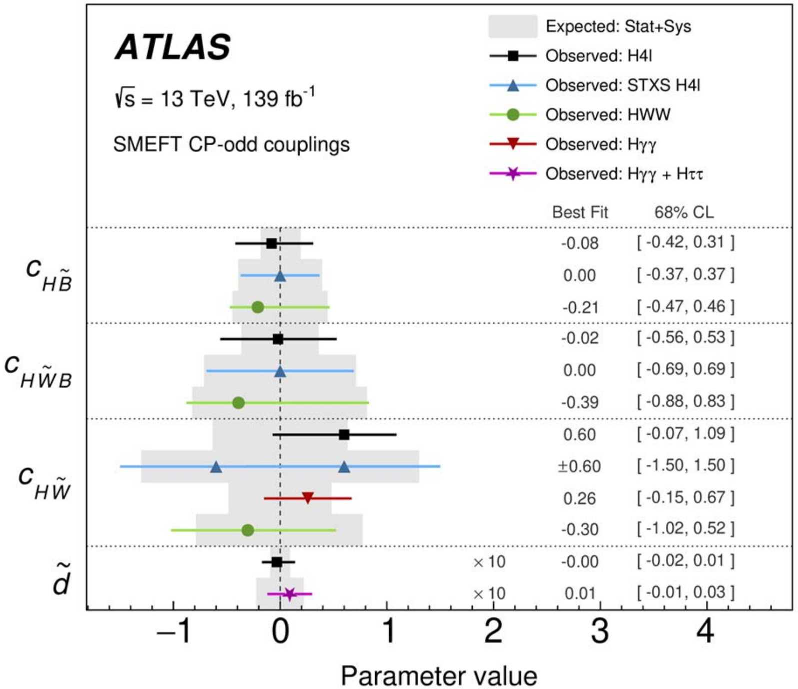
Conclusions

- CP properties: SM: $J^{PC}=0++$

Parity P: Run 1



-Interactions w/ vector bosons
Introduce CP-odd operators in EFT
Warsaw basis: Wilson coefficients
HISZ basis: single parameter



+H→WW*

-w/ fermions:

$$\mathcal{L}_{HFF} = -\frac{m_F}{v}\kappa_F(\cos\alpha\,\bar{\psi}\psi + \sin\alpha\,\bar{\psi}i\gamma_5\psi)H$$

tranverse spin components of τ in H→ττ
CP properties of Htt in ttH production
both exclude CP-odd at >3σ
Run 2 : no deviation from CP-even

Conclusions

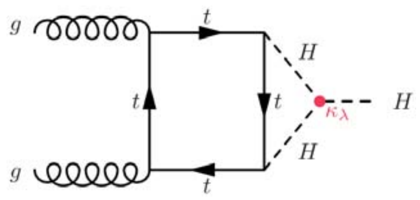
Higgs self-coupling

[superseeding review version]

-HH: combination 95% CL limit: obs: 2.9, exp: 2.4

-Self-coupling constraint from 1-H

(example)



PLB 843 (2023) 137745

Combination assumption	Obs. 95% CL	Exp. 95% CL
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$

Not competitive w/ direct search HH, but allow to relax assumptions on couplings

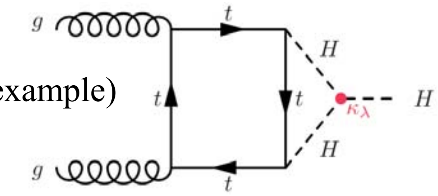
-Search of HHH already started

Conclusions

Higgs self-coupling [superseeding review version]

-HH: combination 95% CL limit: obs: 2.9, exp: 2.4

(example)



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PLB 843 (2023) 137745

Combination assumption	Obs. 95% CL	Exp. 95% CL
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$

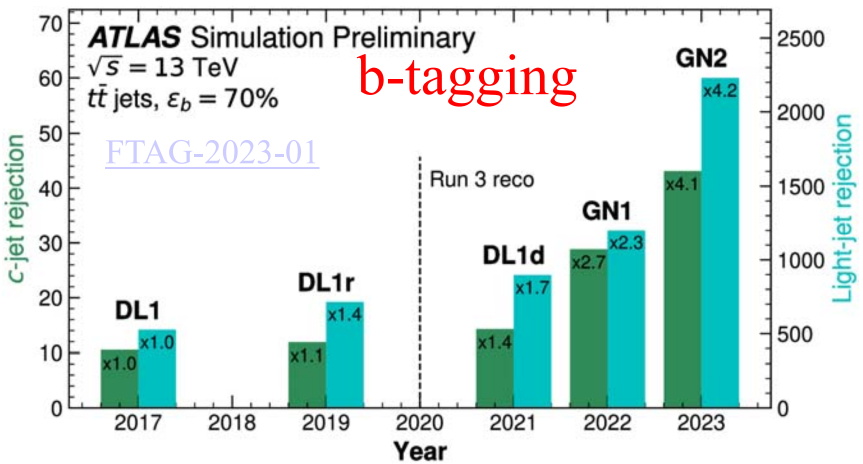
Not competitive w/ direct search HH, but allow to relax assumptions on couplings

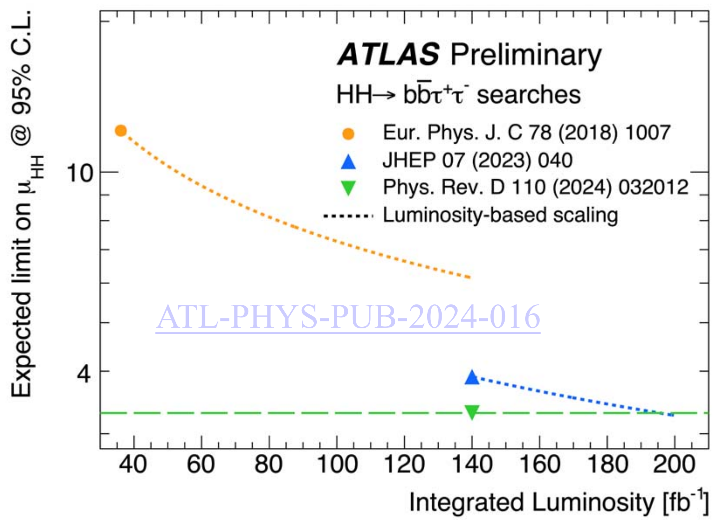
-Search of HHH already started

So far, SM never been faulted in Higgs sector

- Prospects

Run 3: already more stat than Run 2: ∫L, #interaction per bunch crossing, σ (higher energy)





bbττ: illustrative proxy: outperforming expectation

To follow future developments. Thank you for your attention

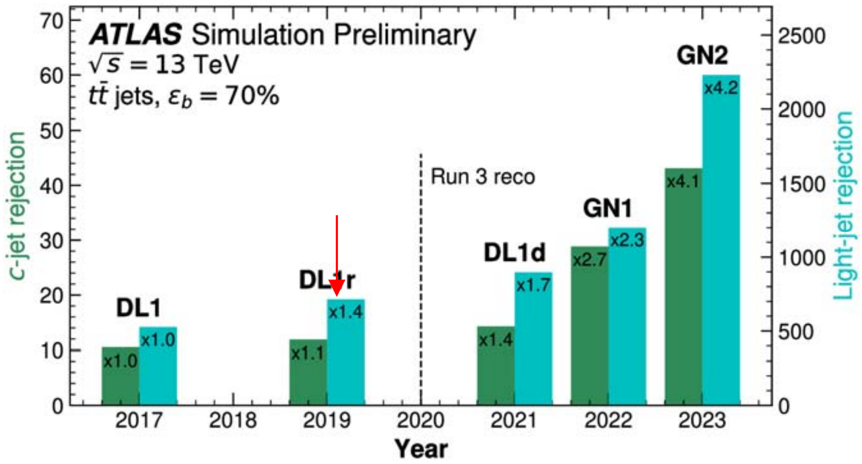
Conclusions & prospects

So far, SM never been faulted in Higgs sector

- Prospects

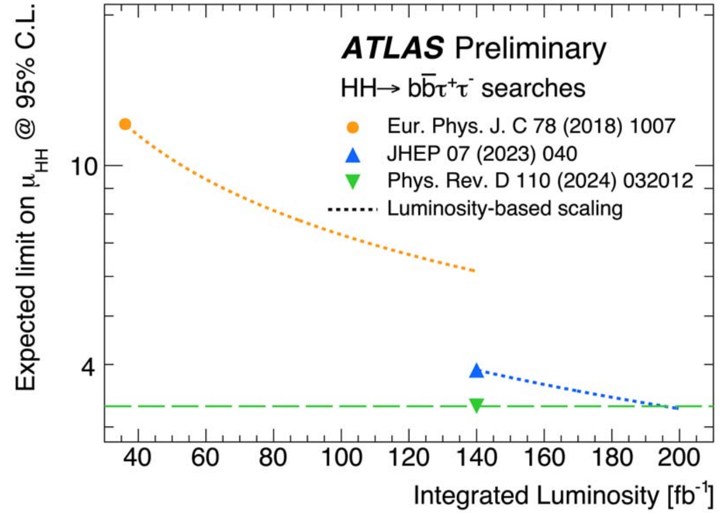
Run 3: -already more stat than Run 2
integrated luminosity
increased #interaction per bunch crossing
Increased cross-section (higher energy)

b-tagging: much improvement already available



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2023-01

bbττ: example proxy for outperforming expectation, ATL-PHYS-PUB-2024-016



To follow future developments
Thank you for your attention